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A report is presented of a program for which the objective was to reduce NO_x mass emissions from a 4000-pound GVW vehicle by extending the operation of the engine in the ultra-lean air/fuel regime. The Phase I effort of the program consisted of a baseline vehicle evaluation with a carburetor, installation of Electronic Fuel Injection (EFI) and the baseline evaluation with EFI and demonstration of present (1970) capability regarding NO_x mass emissions. The Phase II effort consisted of removing the engine from the vehicle and installing it on an engine dynamometer, performing steady-state tests at selected power test points, and, finally, exploring the possible ultra-lean operation using various parameters. The investigations performed during this effort were concentrated at air-fuel ratios of 18:1 and higher. The potential of reducing the NO_x emissions with ultra-lean mixtures is seen clearly. However, ultra-lean mixtures are very prone to misfire resulting in increased HC emissions and rough engine operation giving poor drivability. On the other hand, the oxygen-rich exhaust, resulting from lean operation, appears to offer the possibility of a thermal reactor or a catalyst for oxidizing HC without secondary air. The goal of this program was to extend the lean-limit operation by exploring the effect of the following parameters. (1) Air management (2) Timed sequential injection (3) Spark plug gap, spark duration and energy (4) Intake air heating (5) Intake valve throttling In addition to the above parameters, air/fuel and ignition timing were varied.

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Internal Combustion Engines
Vehicles
Fuel Injectors
Air Intake
Intake Systems
Spark Plugs
Spark Gap

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The
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Control of NO_x Emissions from Mobile Sources

Final Report

April 1972

Contract No. EHS 70-122

Prepared for:

Environmental
Protection Agency

Office of Air Programs

Characterization and
Control Development
Branch

Ann Arbor, Michigan

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FOREWORD

This is the final report on an investigation conducted at the Bendix Research Laboratories for the Environmental Protection Agency under Contract No. EHS 70-122 (BRL Project 2872).

The program was performed by the Vehicle Controls Department under the direction of J. R. Kremidas, Department Manager. The project supervisor was D. D. Barnard. The report was prepared by V. B. Gala who was also the responsible engineer. Significant contributions were made by R. J. Brown of the Simulation and Computation Department, who was responsible for computer programming and data reduction and R. S. Henrich and F. B. Lux of the Control and Data-Handling Systems Department, who designed and built the special ignition and sequential injection control units. Special mention is in order for the valuable technical assistance provided by L. H. Kareus, I. Scott, and C. Adams of the Automotive Test Laboratory.

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TABLE OF CONTENTS

	Page
SECTION 1 - INTRODUCTION	1-1
1.1 Air Management	1-2
1.2 Timed Sequential Injection	1-3
1.3 Spark Plug Gap, Spark Duration and Energy	1-3
1.4 Intake Air Heating	1-3
1.5 Intake Valve Throttling (IVT)	1-3
1.6 Bendix EFI System	1-3
1.7 Special Ignition System	1-5
SECTION 2 - SUMMARY OF TEST RESULTS	2-1
SECTION 3 - TECHNICAL DISCUSSION	3-1
3.1 Baseline Tests	3-1
3.2 Air Management	3-2
3.3 Sequential Injection Timing	3-3
3.4 Spark Energy/Duration and Gap Size	3-7
3.5 Inlet Air Heating	3-11
3.6 Intake Valve Throttling (IVT)	3-12
SECTION 4 - CONCLUSIONS AND RECOMMENDATIONS	4-1
4.1 Conclusions	4-1
4.2 Recommendations	4-2
REFERENCES	
NOMENCLATURE	
APPENDIX A - TEST DESCRIPTION	A-1
A.1 Test Set-Up	A-1
A.2 Data Reduction	A-3
A.3 Test Procedure	A-16
APPENDIX B - AIR-MANAGEMENT EVALUATION OF A 1970 FORD C.I.D. ENGINE WITH AN EFI INTAKE MANIFOLD AND THROTTLE BODY	B-1
APPENDIX C - BASELINE EVALUATIONS OF THE 429 C.I.D. FORD ENGINE WITH BENDIX EFI SYSTEM CALIBRATED FOR ULTRA-LEAN OPERATION	C-1
APPENDIX D - AUTOMOTIVE IGNITION SPARK ENERGY, VOLTAGE AND CURRENT WAVEFORMS STUDY, PHASE I	D-1
APPENDIX E - INLET VALVE THROTTLING CAMSHAFT LOBE ANALYSIS	E-1

d

Page

APPENDIX F - DATA TABULATION F-1

F.1 Baseline Carburetor Tests F-1
F.2 Sequential Injection - I F-4
F.3 Sequential Injection - II F-10
F.4 Ignition Effects F-14
F.5 Inlet Air Heating F-24
F.6 Intake Valve Throttling F-33

LIST OF ILLUSTRATIONS

Figure No.	Title	Page
1-1	Effect of Air-Fuel Ratio on Exhaust Emissions	1-2
1-2	Fuel Injection Timing Diagram	1-4
1-3	Bendix Electronic Fuel Injection System	1-4
1-4	Manual Sequential Injection Control Unit	1-6
1-5	Ignition Variables Control Units	1-6
3-1	Effect of Injection Timing on BSFC, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6:1	3-17
3-2	Effect of Injection Timing on $BSNO_x$, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6:1	3-17
3-3	Effects of Injection Timing on BSHC, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6:1	3-18
3-4	Effect of Injection Timing on BSCO, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6:1	3-18
3-5	Effect of Injection Timing on BSFC, 1200 rpm - 45 b-ft-lbs, A/F = 21:1	3-19
3-6	Effect of Injection Timing on $BSNO_x$, 1200 rpm - 45 b-ft-lbs, A/F = 21:1	3-19
3-7	Effect of Injection Timing on BSHC, 1200 rpm - 45 b-ft-lbs, A/F = 21:1	3-20
3-8	Effect of Injection Timing on BSCO, 1200 rpm - 45 b-ft-lbs, A/F = 21:1	3-20
3-9	Effect of Injection Timing on BSFC, 1200 rpm - 100 b-ft-lbs, A/F = 21.4:1	3-21
3-10	Effect of Injection Timing on $BSNO_x$, 1200 rpm - 100 b-ft-lbs, A/F = 21.4:1	3-21
3-11	Effect of Injection Timing on BSHC, 1200 rpm - 100 b-ft-lbs, A/F = 21.4:1	3-22
3-12	Effect of Injection Timing on BSCO, 1200 rpm - 100 b-ft-lbs, A/F = 21.4:1	3-22
3-13	Effect of Injection Timing on BSFC, 2000 rpm - 70 b-ft-lbs, A/F = 21.8:1	3-23
3-14	Effect of Injection Timing on $BSNO_x$, 2000 rpm - 70 b-ft-lbs, A/F = 21.8:1	3-23
3-15	Effect of Injection Timing on BSCO, 2000 rpm - 70 b-ft-lbs, A/F = 21.8:1	3-24
3-16	Effect of Injection Timing on BSHC, 2000 rpm - 70 b-ft-lbs, A/F = 21.8:1	3-24
3-17	Effect of Injection Timing on BSFC, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1	3-25
3-18	Effect of Injection Timing on $BSNO_x$, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1	3-25
3-19	Effect of Injection Timing on BSHC, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1	3-26
3-20	Effect of Injection Timing on BSCO, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1	3-26

Figure No.	Title	Page
3-21	Current and Voltage Waveforms for 2.8 Millisecond Duration and 80 Millijoules Energy Spark	3-27
3-22	Current and Voltage Waveforms for 5.3 Millisecond Duration and 140 Millijoules Energy Spark	3-27
3-23	Modified Rotor	3-28
3-24	Effect of Spark Plug Gap and Spark Duration/Energy on NO_x Emissions, Engine Speed - 1200 rpm, Torque - 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-29
3-25	Effect of Spark Gap and Duration/Energy on HC Emissions, Engine Speed - 1200 rpm, Torque - 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-29
3-26	Effect of Spark Plug Gap and Spark Duration on NO_x Emissions, Engine Speed - 1200 rpm, Torque - 100 b-ft-lbs, A/F = 20.1:1, Ignition Timing 40° BTDC	3-30
3-27	Effect of Spark Plug Gap and Spark Duration on HC Emissions, Engine Speed - 1200 rpm, Torque - 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-30
3-28	Effect of Spark Plug Gap and Spark Duration on NO_x Emissions, Engine Speed - 640 rpm, Torque - 35 b-ft-lbs (Idle), A/F = 12:1, Ignition Timing - 10° BTDC	3-31
3-29	Effect of Spark Plug Gap and Spark Duration on HC Emissions, Engine Speed - 640 rpm, Torque - 35 b-ft-lbs (Idle), A/F = 12:1, Ignition Timing - 10° BTDC	3-31
3-30	Inlet Air Heating Test Set Up	3-32
3-31	Effect of Inlet Air Temperature on $BSNO_x$, 1200 rpm, 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-33
3-32	Effect of Inlet Air Temperature on BSHC, 1200 rpm, 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-33
3-33	Effect of Inlet Air Temperature on $BSNO_x$ 640 rpm, 35 b-ft-lbs (Idle), A/F = 13.9:1, Ignition Timing - 10° BTDC	3-34
3-34	Effect of Inlet Air Temperature on BSHC, 640 rpm, 35 b-ft-lbs (Idle), A/F = 13.9:1, Ignition Timing - 10° BTDC	3-34
3-35	Effect of Inlet Air Temperature on $BSNO_x$, 1200 rpm, 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-35
3-36	Effect of Inlet Air Temperature on BSHC, 1200 rpm, 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-35

Figure No.	Title	Page
3-37	Effect of Inlet Air Temperature on $BSNO_x$, 2000 rpm, 180 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-36
3-38	Effect of Inlet Air Temperature on BSHC 2000 rpm, 180 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-36
3-39	Effect of Inlet Air Temperature on $BSNO_x$, 2000 rpm, 70 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-37
3-40	Effect of Inlet Air Temperature on BSHC, 2000 rpm, 70 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC	3-37
3-41	Test Results Correlation	3-38

LIST OF TABLES

Table No.	Title	Page
3-1	Summary of the Baseline Carburetor and EFI Results	3-3
3-2	Summary of Ignition Parameters	3-9
3-3	Summary of the Baseline and Best Parameter Results	3-14
3-4	Summary of the Best Parameter Results with the Intake Valve Throttling	3-16

SECTION 1

INTRODUCTION

The work for this project was undertaken under EPA Contract No. EHS 70-122. The objective of this program was to reduce NO_x mass emissions from a 4000-pound GVW vehicle by extending the operation of the engine in the ultra-lean air/fuel regime. A 1970 Ford Thunderbird with a 429 CID engine (compression ratio of 10.5:1) was obtained for this purpose.

The Phase I effort of the program consisted of a baseline vehicle evaluation with a carburetor, installation of Electronic Fuel Injection (EFI) and the baseline evaluation with EFI and demonstration of present (1970) capability regarding NO_x mass emissions.

The Phase II effort consisted of removing the engine from the vehicle and installing it on an engine dynamometer, performing steady-state tests at selected power test points, and, finally, exploring the possible ultra-lean operation using various parameters.

The selection of the steady-state power set points was based on power set points encountered during the 1970 FTP* driving cycle.

The following five power set points were selected:

(1) 640 rpm, 35 b-ft-lbs

(2) 1200 rpm, 45 b-ft-lbs

(3) 2000 rpm, 70 b-ft-lbs

(4) 1200 rpm, 100 b-ft-lbs

(5) 2000 rpm, 180 b-ft-lbs

The first three power set points represent steady-state conditions of idle in drive, 30 mph cruise and 50 mph cruise conditions. The power set points 4 and 5 represent conditions encountered during smooth acceleration from 0 to 30 mph and 15 to 50 mph speeds, respectively.

Figure 1-1 shows the typical effect of A/F on HC, CO and NO_x emissions. The investigations performed during this effort were concentrated at air-fuel ratios of 18:1 and higher. The potential of reducing the NO_x emissions with ultra-lean mixtures is seen clearly. However, ultra-lean mixtures are very prone to misfire resulting in increased HC emissions and rough engine operation giving poor drivability. On the other hand, the oxygen-rich exhaust, resulting from lean operation, appears to offer

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*A list of nomenclature is given at the end of the report.

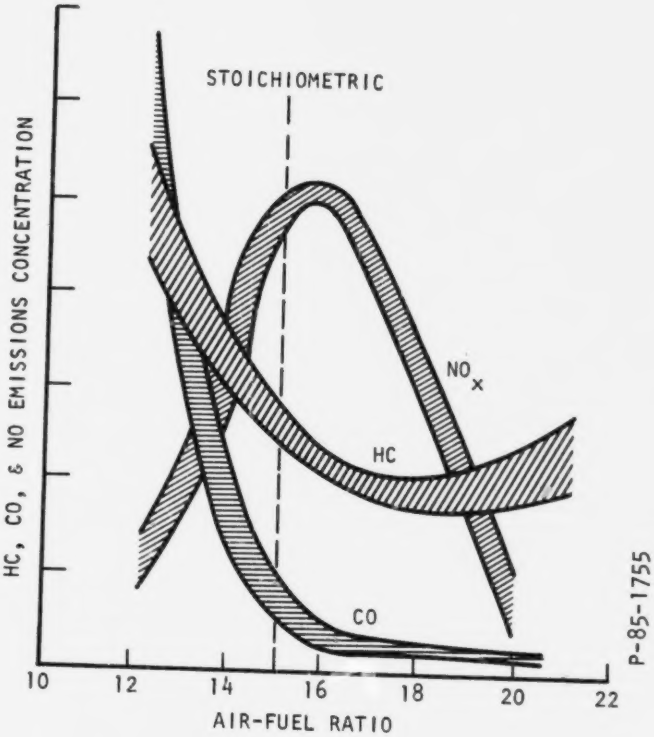

Figure 1-1 - Effect of Air-Fuel Ratio on Exhaust Emissions

the possibility of a thermal reactor or a catalyst for oxidizing HC without secondary air. The goal of this program was to extend the lean-limit operation by exploring the effect of the following parameters.

(1) Air management

(2) Timed sequential injection

(3) Spark plug gap, spark duration and energy

(4) Intake air heating

(5) Intake valve throttling

In addition to the above parameters, air/fuel and ignition timing were varied.

"Lean-limit" is generally defined as extremes of air/fuel where a minimum of misfire occurs. To simplify the determination of "lean-limit" and to ensure extremes of the lean air/fuel, the "lean-limit" was defined as the air/fuel where the HC concentrations in the exhaust are about 12,000 ppm, expressed as carbon equivalent. Previous experience at Bendix has shown that enleanment of more than an additional 0.5 A/F beyond this point will result in misfire.

1.1 AIR MANAGEMENT

Lean-limit operation of an engine becomes limited if only one of the cylinder misfires because it is running lean compared to other cylinders. Therefore, even distribution of air and fuel to each cylinder would contribute significantly in extension of the lean limit. Since fuel distribution can be controlled very precisely with EFI, the air distribution becomes of significant importance. The intake and the exhaust manifolds contribute to mass air flow distribution. Therefore, the objective of this task was to evaluate the intake and the exhaust manifolds for their role in distribution of mass air to individual cylinders and correct non-uniformities if possible. Motored-engine tests were performed to evaluate the intake manifold while operating engine tests with EFI were performed to evaluate the exhaust manifolds.

1.2 TIMED SEQUENTIAL INJECTION

The standard Bendix EFI system is described as a timed, intermittent, two-group, port injection system. This means that fuel is injected into the intake manifold (just upstream of the intake valve) once per engine cycle but that only two injection signals are furnished per cycle. That is, the eight injectors are divided into two groups of four. The injectors in a given group are selected to correspond to four cylinders that fire in sequence. Two-group injection is one of several alternatives to fully timed sequential injection.

In group injection, the four injectors in a group fire simultaneously. This means that only one of the corresponding cylinders for that group can receive fuel at the optimum time in the engine cycle. The leading cylinder is normally selected for establishing the timing signal so the fuel for the remaining three cylinders is injected earlier than optimum by 90 degrees, 180 degrees and 270 degrees of crank angle, respectively.

In sequential injection a timing signal is established for optimum injection and furnished to each injector sequentially allowing every injector to fire separately. Therefore, each cylinder can receive fuel at an optimum time in the engine cycle.

During this part of the investigation, a sequential injection control was used and injection timing was varied within the range shown in Figure 1-2 to evaluate the effect of injection timing on emissions and extension of the lean limit of operation. The selected injection timing points are described in the figure as A, B, and C.

1.3 SPARK PLUG GAP, SPARK DURATION AND INTENSITY

Spark plug gap, spark duration and intensity have been shown previously to affect engine performance and exhaust emissions at light loads (1, 2).* This is thought to be due to an increase in the probability of reaching an ignitable mixture at very lean air-fuel ratios.

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*Numbers in parentheses designate References at the end of the report.

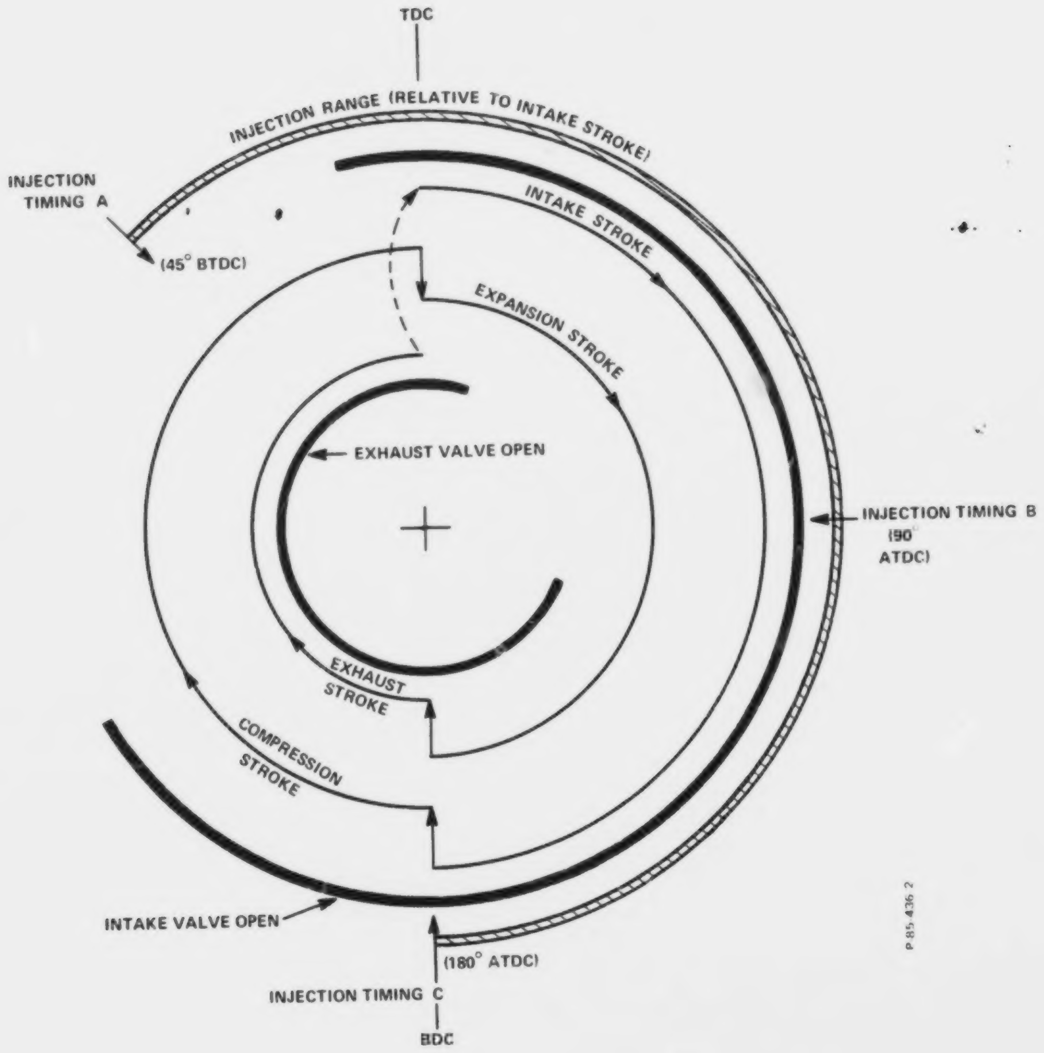
TDC
INJECTION RANGE (RELATIVE TO INTAKE STROKE)
INJECTION TIMING A
(45° BTDC)
INTAKE STROKE
EXPANSION STROKE
EXHAUST VALVE OPEN
INJECTION TIMING B
(90° ATDC)
EXHAUST STROKE
COMPRESSION STROKE
INTAKE VALVE OPEN
(180° ATDC)
INJECTION TIMING C
BDC
P 85 436 2

Figure 1-2 - Fuel Injection Timing Diagram

The objective of this investigation was to combine the effects of timed sequential injection with a study of variations of ignition parameters to extend the lean limit of operation for the selected power set points.

1.4 INTAKE AIR HEATING

The objective here was to evaluate the effect of heating the intake air on the extension of the lean limit, emissions and engine performance when combined with the best timed sequential injection, best spark plug gap and spark duration obtained previously. It was also intended to obtain a "best" parameter combination from these data for comparison with the baseline tests.

1.5 INTAKE VALVE THROTTLING (IVT)

By limiting the lift of the intake valve, air can be throttled at the intake valve instead of at the throttle plates. By throttling the air at the intake valve, turbulence is created in the combustion chamber and increased turbulence is known to extend the lean limit operation (3). To limit the lift, three specially ground camshafts were used. The IVT tests were performed using the "best" spark plug gap and the "best" spark duration/energy along with the "best" sequential injection timing.

1.6 BENDIX EFI SYSTEM

Figure 1-3 shows the components and typical installation of the standard two-group injection system on an automobile.

Fuel from the tank is pumped (5) through the filter (6) to the common fuel rail (9) which supplies all injectors (1). The fuel-pressure control valve (4) maintains a constant pressure drop of 39 psid between the rail and the intake manifold and returns excess fuel and purged vapors to the fuel tank. The fuel is injected upstream of the intake valves.

Information from the sensors (3 and 8) is fed into the electronic control unit (7) which regulates the injectors. The trigger unit (7) provides the electronic control unit with timed signals which initiate injection and a pulse rate with which engine speed is computed.

The Bendix Electronic Fuel Injection System (EFI) meters fuel in proportion to the mass of air taken in during each engine cycle. Measuring the mass flow of air is achieved by using "speed-density" sensing. The mass of air taken in by a cylinder per cycle in a given engine is a function of the pressure and temperature of the air in the intake manifold, the amount of residual exhaust gas in the cylinder and the intake valve pressure drop during induction. At any manifold pressure, residual exhaust gas and intake valve pressure drop are a function of RPM. Thus, measurement of manifold pressure, temperature and engine RPM, known as speed-density sensing, tells the electronic control unit (ECU) how much fresh air will be taken in per engine cycle.

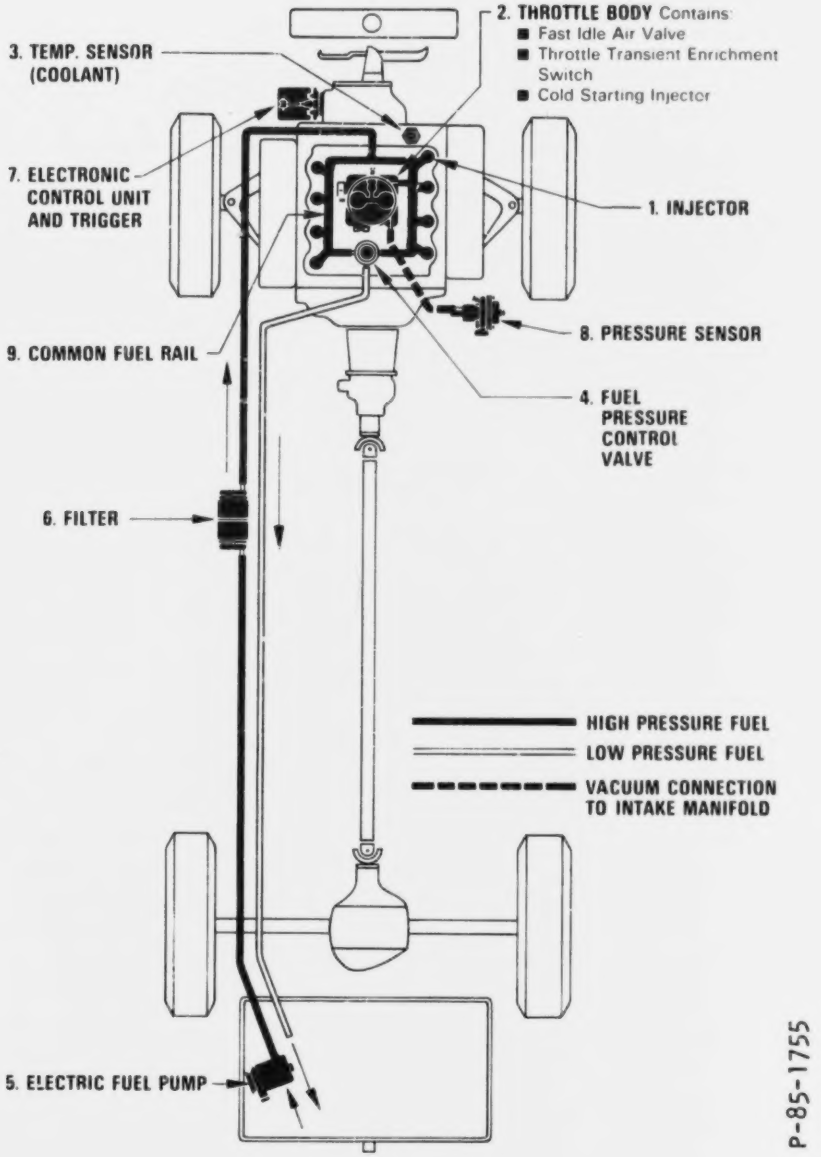
2. THROTTLE BODY Contains:
■ Fast Idle Air Valve
■ Throttle Transient Enrichment Switch
■ Cold Starting Injector
3. TEMP. SENSOR (COOLANT)
7. ELECTRONIC CONTROL UNIT AND TRIGGER
1. INJECTOR
8. PRESSURE SENSOR
9. COMMON FUEL RAIL
4. FUEL PRESSURE CONTROL VALVE
6. FILTER
HIGH PRESSURE FUEL
LOW PRESSURE FUEL
VACUUM CONNECTION TO INTAKE MANIFOLD
5. ELECTRIC FUEL PUMP
P-85-1755

Figure 1-3 - Bendix Electronic Fuel Injection System

The ECU electronically computes the duration of open time necessary for the solenoid-operated injector valves to provide the precise amount of fuel required for each cycle.

To conduct steady-state tests on the engine dynamometer, a special ECU was built which allowed variable-timing sequential injection and manual control of the injector pulse width. Figure 1-4 shows the control unit. A special electronic trigger was employed in conjunction with the ECU to allow sequential injection. The trigger unit was housed in an externally mounted distributor driven by the engine at the engine camshaft speed. The trigger provided signals in sequence of the engine firing order to the ECU to initiate injection. It also provided means for changing the injection timing.

1.7 SPECIAL IGNITION SYSTEM

A special ignition control system was designed and constructed to vary spark duration and energy. The system is basically a capacitor-discharge (CD) type. It differs from the standard CD system in that the system discharges the capacitor a controlled number of times for one ignition period. Controls are provided to vary the spark intensity, the ignition duration and the period between sparks. The period between the sparks can be made small enough so that a continuous spark will occur. Figure 1-5 shows the control units.

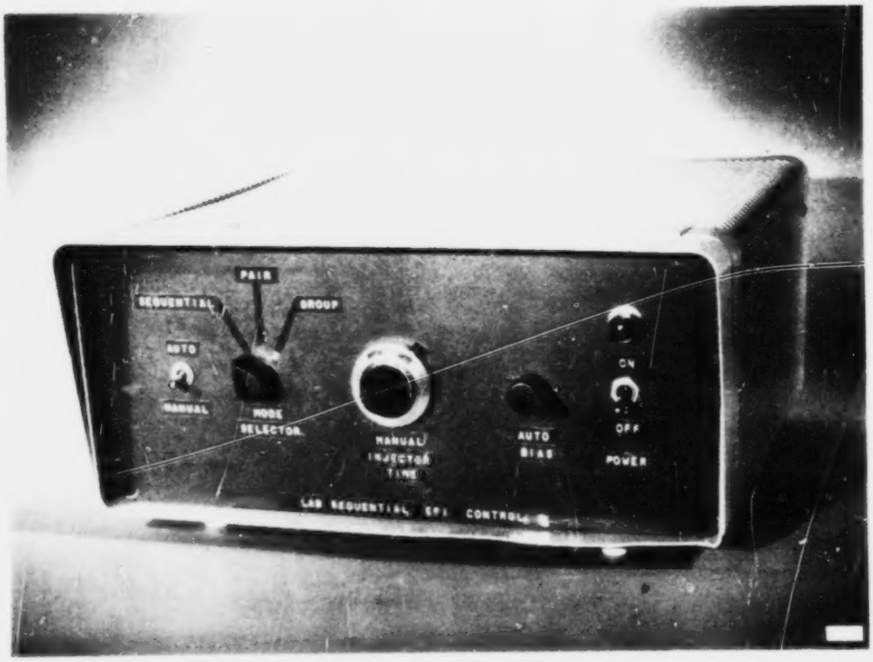
PAIR
SEQUENTIAL
GROUP
AUTO
MANUAL
MODE
SELECTOR
MANUAL
INJECTOR
TIME
AUTO
BIAS
ON
OFF
POWER
LAB SEQUENTIAL EFI CONTROL

Figure 1-4 - Manual Sequential Injection Control Unit

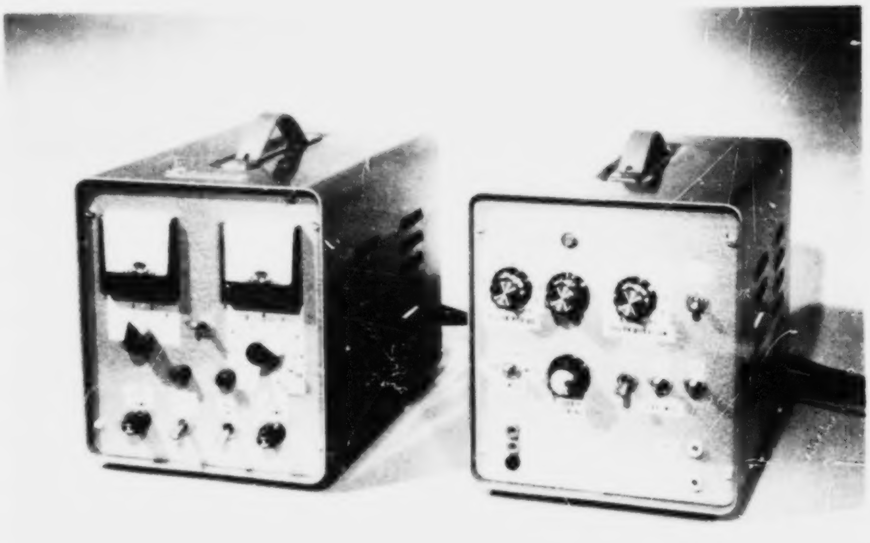

Figure 1-5 - Ignition Variables Control Units

SECTION 2

SUMMARY

A standard carbureted vehicle (Ford Thunderbird with a 10.5:1 C.R. 429 C.I.D. engine) was baseline emission tested before and after 4000 miles of operation. It was then equipped with a Bendix Electronic Fuel Injection System having a basically ultra lean A/F calibration (nominally 20:1). Emissions were measured again after the EFI installation with the following results: NO_x mass emissions were reduced from 4.4 gm/mile to 1.5 gms/mile, CO emissions increased from 21.2 gms/mile to 22.0 gm/mile and HC emissions increased from 2.1 gms/mile to 2.3 gms/mile. All the tests were performed according to the 1970 FTP. Thus with a lean calibrated EFI, a reduction of 66 percent in NO_x emissions was achieved compared to a standard carbureted vehicle without markedly affecting the CO and HC emissions. However, the vehicle did suffer a substantial loss of satisfactory drivability attributed to a non-optimized EFI calibration and acceleration fuel enrichment circuit.

The engine with EFI was then installed on a dynamometer for a series of parametric investigations for extending the lean limit of operation to reduce NO_x. The vehicle EFI electronic control unit was replaced with a manual control unit. Tests were run at idle, 1200 rpm for two values of brake torque and at 2000 rpm for two values of brake torque.

The production intake and exhaust manifolds were evaluated to determine their influence on uniform inlet air flow between cylinders and it was determined that they do not adversely affect mass air flow distribution among the cylinders for the engine speeds and loads considered in this project. Therefore, the remainder of the parametric tests were performed using the standard intake and exhaust manifolds.

A control was fabricated to provide variable timed fully sequential injection and three different injection timing points were evaluated to determine what effect, if any, timing had on extending the lean limit.

Of the three injection timings considered, 45° BTDC (intake) was found to be the best for extending the lean limit of operation and in reducing NO_x mass emissions at idle and 1,200 rpm. With this injection timing, the fuel was injected on a closed intake valve where it normally vaporizes before being drawn into the cylinder. The results obtained with this injection timing were not significantly different from the results obtained with the standard two group injection timing. With a sequential injection timing of 90° ATDC (intake), the injection occurred when the intake valve was wide open. This was found to have a tendency to wet the spark plugs and increased the tendency to misfire.

As a result, HC mass emissions were higher and the lean limit air-fuel ratios were relatively richer than with the other two timings. Thus NO_x mass emissions were higher. With a timing of 180° ATDC (intake), the fuel was injected just before the intake valve closed. This allowed the maximum residence time for the fuel prior to being inducted into the cylinder. The long residence time allowed more complete vaporization of the fuel and improved combustion. Because of the improved combustion, for a given air/fuel and ignition timing, HC mass emissions were lower than for the other two injection timings and the lean limit was extended; however, NO_x mass emissions were higher due to improved thermal efficiency. Thus, the injection timing of 45° BTDC (intake) was judged to be the "best" overall sequential injection timing.

Similar general trends were observed for the 2,000 rpm test points. However, the difference in emissions for different injection timings was small for the 2,000 rpm test points compared to the results at idle and 1,200 rpm. At 2,000 rpm higher turbulence exists and a high energy and long duration spark was used. Both of these factors helped to provide more efficient combustion. Thus, the effect of injection timing on combustion was minimal for most of the tests performed at 2000 rpm.

A special ignition control was fabricated that provided a variable spark duration and energy. The purpose was to evaluate the effect of spark characteristics and spark plug gap on extension of the lean limit because it had veen reported that improvements were possible when the air-fuel ratios were very lean.

The tests were performed at idle and at the 1,200 rpm set points to determine "best" spark plug gap and the "best" spark energy/duration for minimum NO_x mass emissions. Increasing the spark plug gap from 0.035 inches (standard) to 0.045 inches and then to 0.060 inches had a similar effect on exhaust mass emissions as increasing the spark duration from 1.35 milliseconds (standard) to 2.8 milliseconds and then to 5.3 milliseconds.

For example, at 1,200 rpm, 45 b-ft-lbs torque, increasing the spark plug gap to 0.045 inches from 0.035 inches, resulted in $BSNO_x$ and BSHC reductions of about 33 percent and 47 percent, respectively, for an A/F of 20:1 and ignition timing of 40° BTDC (MBT).

At the same test condition, when the spark duration was increased to 2.8 milliseconds from 1.35 milliseconds, the reduction in $BSNO_x$ and BSHC was about 28 percent and 22 percent, respectively. With the gap further increased to 0.060 inches, $BSNO_x$ emissions increased almost 59 percent and BSHC emissions decreased 58 percent as compared to results for a 0.035 inch gap. Similarly, increasing the spark duration to 5.3 milliseconds increased $BSNO_x$ 27 percent and decreased BSHC 57 percent from values for a standard gap and spark duration. Similar trends were observed for other air/fuel and ignition timings and also for the 1,200 rpm, 100 b-ft-lbs torque set point. For both set points, the effect on $BSNO_x$ and BSHC due to changes in gap and spark duration was reduced at higher air/fuel (22:1) and retarded timing (25° BTDC, 15° BTDC).

At idle an increased spark plug gap had an effect similar to that for extended spark duration. However, increasing the gap and spark duration increased BSHC emissions and decreased $BSNO_x$ emissions. For example, at an A/F of 21:1 and ignition timing of 10° BTDC, increasing the gap from 0.035 inches to 0.045 inches and then to 0.060 inches increased BSHC emissions to 32 percent and 51 percent respectively. Similarly, increasing the spark duration to 2.8 milliseconds and then to 5.3 milliseconds from 1.35 milliseconds increased BSHC 39 percent and 60 percent, respectively. When the gap was changed to 0.045 inches and then to 0.060 inches from 0.035 inches, $BSNO_x$ decreased 42 percent and 52 percent, respectively. When spark duration was changed to 2.8 milliseconds and then to 5.3 milliseconds from 1.35 milliseconds, $BSNO_x$ decreased about 38 percent in both cases.

Increased spark duration/energy increased the tendency of detonation at 1,200 rpm, 100 b-ft-lbs and 2,000 rpm, 180 b-ft-lbs.

An inlet air heater was installed to enable an evaluation of the effect of air temperature on extension of the lean limit. Temperatures to 150°F were investigated. In general, increased inlet air temperature extended the lean-limit of operation. Depending on the engine operating condition, the lean-limit was extended as far as an A/F of 26:1. Again, depending on the engine operating condition, increasing the inlet air temperature decreased BSHC emissions by as much as 55 percent while at the same time $BSNO_x$ emissions increased by as much as 100 percent. For inlet air temperatures greater than or equal to 150°F, the tendency for detonation increased for the set points of 1,200 rpm, 100 b-ft-lbs and 2,000 rpm, 180 b-ft-lbs.

Three specially ground camshafts were installed to provide air throttling by the intake valves rather than the usual manifold inlet butterfly valve. This was expected to increase turbulence and promote better combustion (Reference 3).

Intake valve throttling (IVT) caused the MBT spark timing to occur as much as 15° nearer to TDC. Depending on the operating condition, IVT caused an increase in $BSNO_x$ of as much as four times the value obtained without it. The expected lean-limit extension was not realized for all the power set points because of an increase in BSHC. The tendency toward detonation was increased. With manifold fuel injection and IVT, even distribution of the air/fuel mixture among the cylinders may pose a problem.

As a result of the above series of parametric tests, it was concluded that the original objective of lowering NO_x mass emissions to less than 1.3 gms/mile would be easily achieved. The excess CO and HC would have to be converted with exhaust treatment devices. For this, the excess and hot O_2 in the exhuast could be helpful. Sequential injection was not shown to be effective and heated inlet air does not appear to be practical since it increases the NO_x mass emissions. It does appear that a higher energy spark would be desirable where lean operation is used. IVT demonstrated no significant improvements and it seems to be an inherently expensive control method.

It was recommended that intake manifold design be optimized for installations with fuel injection to assure air delivery uniformity over a greater range of operation. The effects of some of the parameters should be studied for engine transient conditions and optimum combinations of EGR and lean A/F should be explored to effect further control of NO_x.

SECTION 3

TECHNICAL DISCUSSION

3.1 BASELINE TESTS

Two sets of baseline tests were run. One set consisted of emissions tests on a vehicle, run according to the 1970 Federal Test Procedure, with the standard carburetor as well as with the lean-calibrated Bendix EFI system installed. Two tests were run with the carbureted vehicle at the EPA facilities in Ypsilanti, Michigan. The first test was performed on a new vehicle and the second test was performed after driving the vehicle for 4,000 miles over a previously established driving cycle. The results for the carbureted vehicle are summarized below:

	NO_x(gm/mile)	CO(gm/mile)	HC(gm/mile)
New Vehicle	5.4	15.8	2.0
After 4,000 miles	4.4	21.2	2.1

After installing the EFI, 1970 FTP tests were performed at Bendix with the following results:

	NO_x(gm/mile)	CO(gm/mile)	HC(gm/mile)
Test #1	1.38 (1.18)	22.1	3.1
Test #2	1.22 (1.21)	19.7	3.1

The NO_x emissions were converted from concentrations to a mass basis using the "then proposed" federal standards for 1972. At the time of the tests no adopted standards for NO_x existed. Because of this the NO_x mass emissions values listed above and below for the tests of the EFI equipped vehicle are shown with and without a humidity correction. The humidity corrected values are given in parentheses and were computed from recorded conditions at the time of the test using the correction factor described in Federal Register No. 228 dated November 25, 1971.

After the vehicle was tested by Bendix, it was delivered to EPA where another set of 1970 FTP tests were performed with the following results:

	NO_x(gm/mile)	CO(gm/mile)	HC(gm/mile)
Test #1	1.6 (1.45)	21.0	2.3
Test #2	1.5 (1.37)	22.0	2.3

It can be seen that, although the tests at Bendix produced the expected values of NO_x mass emissions (less than 1.3 gm/mile), the EPA tests did not. In addition, the driveability evaluations made by EPA personnel were unfavorable (Reference 5). The poor driveability resulted from the fact that the EFI control and calibrations had not been optimized. With the basically lean A/F calibration, the vehicle is very sensitive to the warm-up characteristics and to the acceleration enrichment. The performance of these subsystems at the time was less than adequate. Additional time spent in calibration would have resulted in improved driveability.

The differences in the results between the two facilities can probably be attributed to variations between drivers, equipment and instrumentation.

The second set of baseline tests consisted of steady-state tests on an engine dynamometer at the five selected set points. Appendix C describes the baseline tests along with sample calculations and the results obtained with EFI. At the end of the program, after re-installing the carbureted manifold, the baseline tests were run again. The results are tabulated in Appendix F under "Baseline Carburetor Tests." The results are summarized in Table 3-1 for convenience.

3.2 AIR MANAGEMENT

Ultra-lean operation of a spark ignition engine can reduce NO_x emissions. However, ultra-lean operation, without a misfire, requires, among other things, that all cylinders be supplied with the same quantity of air-fuel mixture and that the mixture be maintained at a constant air/fuel ratio.

The Bendix Electronic Fuel Injection (EFI) system can be calibrated to give uniform fuel distribution to the individual cylinders to within one percent of one another. Therefore, in the EFI-equipped engine, the uniform distribution of the mass air flow to the individual cylinders is an important factor in maintaining a constant air/fuel ratio among the cylinders.

As a part of this program, the standard intake and exhaust manifolds were evaluated for their role in distribution of the mass air flow. To evaluate the intake manifold, motored-engine tests were conducted and certain parameters were measured for use with an analytical technique.

Once the intake manifold was evaluated and found to provide satisfactory air distribution, tests were performed on the operating engine to evaluate the exhaust manifolds. Individual cylinder exhaust was sampled to determine the air/fuel at each cylinder. To determine the effect of the standard exhaust manifolds on air/fuel at each cylinder, cylinder-to-cylinder air/fuel was first determined using a set of tuned exhaust headers as a baseline. It was assumed that these headers would have a minimum effect on air/fuel from cylinder-to-cylinder. The results

Table 3-1 - Summary of the Baseline Carburetor and EFI Results

	Speed rpm	Torque b-ft-lbs	BSFC	BSNO$_x$	BSCO	BSHC
			lb/b-hp-hr	gm/b-hp-hr		
EFI	640	35	1.45	1.3	131.20	8.20
Carburetor	640	35	1.25	1.94	14.97	0.84
EFI	1200	45	1.41	0.89	25.20	4.70
Carburetor	1200	45	0.89	4.25	12.04	1.95
EFI	1200	100	0.77	0.59	70.55	2.85
Carburetor	1200	100	0.53	5.25	6.70	2.50
EFI	2000	70	0.8	1.49	7.99	3.61
Carburetor	2000	70	0.65	11.93	7.63	1.74
EFI	2000	180	0.48	2.4	9.65	0.69
Carburetor	2000	180	0.43	12.35	5.18	4.13

P-85-436-2

were then compared with the air/fuel measurements from each cylinder using the standard manifolds. Appendix B discusses the air management task in detail.

It was concluded from these studies that, for the engine operating range to be used for this project, the standard intake and exhaust manifolds were satisfactory for uniform mass air flow distribution to individual cylinders. Also it was observed that sequential injection did not provide a more uniform air/fuel cylinder-to-cylinder, than the standard group injection EFI. Therefore, merely converting an EFI system to sequential injection will not enable any leaner operation than standard group injection and thus there will not be any reduction in NO$_x$ emissions. It will be shown later, however, that if not timed properly, sequential injection could have an adverse effect on emissions and performance of the engine.

3.3 SEQUENTIAL INJECTION TIMING

The purpose of this study was to evaluate the effect of timed sequential injection (when set to inject at different crank angles with respect to the opening of the intake valve) on emissions and on lean-limit extension without misfire. Also, it was intended to compare the timed sequential injection with group injection for performance and emissions.

A special electronic control unit was designed and constructed to allow sequential injection. Also, a special trigger was fabricated and housed in a distributor to allow easy changing of the injection timing. The control unit was a manual type which allowed variation of the injector pulse width to vary the air/fuel as desired. The control unit did not have the capability to perform during transient conditions.

Three injection timings were selected to evaluate effects of sequential injection on emissions and extension of the lean-limit operation. The injection timings used were 45° BTDC, 90° ATDC and 180° ATDC. The TDC referred to is relative to the start of the intake stroke as shown previously in Figure 1-2. The selection of these injection timings was based on previous experience at Bendix. The injection timing of 45° BTDC (intake) initiated injection when the intake valve was closed, but the exhaust valve was still open. Timing at 90° ATDC (intake) initiated the injection when the intake valve was wide open and the exhaust valve was closed, and 180° ATDC (intake) timing initiated injection when the intake valve was still open, the exhaust valve closed and the piston at BDC.

For a given speed and torque, the injection timing was set and the air/fuel and the ignition timings varied. The air/fuel was varied from 18:1 to the lean limit in increments of two air/fuel ratios. The lean limit was defined as the occurrence of a hydrocarbon concentration in the exhaust of about 12000 PPM, expressed as carbon equivalent. Such a high number for hydrocarbon concentration was selected to ensure extremes of lean operations. For each injection timing, MBT spark timing was found. Data were also taken for spark timings of MBT-15 degrees and MBT-25 degrees. Since the MBT was different for each injection timing, this approach of varying ignition timing gave a more realistic comparison.

The sequential injection task was coordinated with the special ignition task to make sure that the effects of one on the other could be realized. First, using the standard ignition system, tests were run to determine best injection timings for 1200 rpm, 45 b-ft-lbs; 1200 rpm, 100 b-ft-lbs and 640 rpm, 35 b-ft-lbs (idle) power settings. The best injection timing thus obtained was then fixed and tests were performed to specify best spark plug gap, and spark energy/duration. The sequential injection tests were repeated with these best ignition parameters to see if the ignition parameters had any bearing on the best injection timing determined earlier. The special ignition task is discussed in the next section.

Results were somewhat scattered at idle. Difficulty in setting up the low torque and air/fuel at idle could account for this. The air/fuel is difficult to set at idle because very small air flow and fuel flow are involved.

For the purpose of discussion, the injection timings will be identified as follows:

45° BTDC (intake) - A

90° ATDC (intake) - B

180° ATDC (intake) - C

When the tabulated data is considered, certain trends are seen. The emissions results for timings "A" and "C" have the same trends, but timing "B" has definitely different trends. For a given air/fuel and ignition timing, "C" offers least NO_x mass emissions. However, it is timing "A" which allows leanest operation (up to 20:1 air/fuel at 0° BTDC ignition timing). Timing "B" does not allow operation beyond 16:1 air/fuel at 0° BTDC ignition timing without an unacceptable increase in HC mass emissions.

When compared with the standard group injection and standard ignition timing of 6° BTDC, none of the injection timings or the ignition timings had as low NO_x emissions as did the group injection. However, lower fuel consumption and lower CO emissions were realized with timings "A" and "C" for all ignition timings and with "B" for 10° BTDC and 20° BTDC ignition timings. Figures 3-1 through 3-4 show these comparisons.

Reviewing the tabulated data on page F-5, tests 1 through 9, it can be seen that for the same HC levels as obtained with group injection, with injection timing A, the engine could idle at 0° BTDC ignition timing and an air/fuel of nearly 20:1 (test No. 7). This would reduce NO_x mass emissions to 0.78 gm/b-hp-hr compared to 1.3 gm/b-hp-hr with the group injection. BSFC would go up to only 1.55 lb/b-hp-hr compared with 1.45 lb/b-hp-hr with group injection and CO emissions would be only about 20 gm/b-hp-hr compared with 131 gm/b-hp-hr with group injection. Similar results could be obtained with 10° BTDC ignition timing with somewhat higher HC mass emissions. Thus, injection timing "A" was selected for idle operation for the unknown. It should be kept in mind, however, that selection of such a high air/fuel would probably give a very poor idle quality

The effect of injection timing can be seen more clearly by reviewing the 1200 rpm and 45 b-ft-lbs torque set point.

Generally speaking, injection timing "A" gives least NO_x mass emissions. Injection timing "B" has relatively low NO_x emissions; however, HC and CO emissions and BSFC are higher. Injection timing "C" has much higher NO_x emissions but HC emissions are lower. The lean limit of operation with each injection timing is about the same.

With injection timing "B", fuel is injected when the intake valve is wide open. This apparently wets the spark plugs with the fuel spray. As a result, tendency to misfire increases and HC and CO emissions are higher. On the other hand, with timing "C" the fuel is sprayed on the intake valve as it is about to be closed, and remains on the intake valve for almost 500 degrees of crankshaft rotation. This residence time allows the fuel to vaporize and thus a well-mixed charge of air and fuel is inducted resulting in better combustion. The improved combustion reduces HC but increases NO_x emissions. Despite the better combustion there is no significant extension of the lean limit of operation.

From Figures 3-5 through 3-8 in comparison with group injection, it can be seen that the results obtained with sequential injection timing "A" and an ignition timing of MBT-25° (15° BTDC) would be very much the same, if the ignition timing was further retarded to be the same as standard timing with group injection; namely, 12° BTDC.

From Figure 3-6 the effect of injection timing is seen to be more prominent at the MBT ignition timing; however, with retarded ignition, the injection timing does not have much effect on NO_x emissions. Thus, of the three injection timings selected, "A" gives best results. The results, however, are not much different than obtained with group injection.

For the test condition at 1200 rpm and 100 b-ft-lbs torque, injection timing "C" seems to produce less NO_x. The reason for this is not known. Injection timing "B" still performs poorly. Figures 3-9 through 3-12 show results of sequential injection in comparison with group injection. The difference in performance and emissions is significant at air/fuel of 18:1 and 20:1. For higher air/fuel however, injection timings "A" and "C" have similar results. Injection timing "B" has higher HC emissions and a lower lean limit. Since injection timing "A" allowed the leanest operation and since it was anticipated that the best parameter combination would have ultra-lean air/fuel, injection timing "A" was selected for the rest of the tests.

Using injection timing "A", a study was made to determine best ignition parameters. The spark plug gap, the spark duration and energy were the selected ignition parameters. To observe the effect of ignition parameters on best injection timing, tests were run to re-evaluate sequential injection timings using best ignition parameters. Set points of 2000 rpm, 70 b-ft-lbs torque and 2000 rpm, 180 b-ft-lbs torque were selected for this task.

The data are tabulated in Appendix F under "Sequential Injection - II. For neither set point did injection timing "B" stand out as giving bad performance or emissions results. Two reasons could be given for this. At 2000 rpm, the induction air velocities are much higher causing the fuel to atomize which would lessen the wetting of the spark plugs. The second reason is that with these tests very high ignition energy and spark duration were used. The higher energy and duration would tend to fire even a wet plug.

Also, the injection timing does not seem to influence MBT ignition timings. In all of the cases, MBT was found to be 40° BTDC. This indirectly shows that, in the case of the 2000 rpm test points and high energy/duration spark, injection timing does not have much effect on the combustion process. This can be seen from the tabulated data and Figures 3-13 through 3-20 where sequential injection results are compared with group injection results.

For 2000 rpm, 70 b-ft-lbs torque, some difference in NO_x emissions were observed at air-fuel ratios of 18:1 and 20:1 for MBT ignition timing. However, for leaner air-fuel ratios and retarded ignition timing the differences are small. Figures 3-13 through 3-16 show these comparisons, including results for group injection at an air-fuel of 21.8:1 and various ignition timings.

For 2000 rpm - 180 b-ft-lbs torque, similar observations can be made.

Injection timing "C" was observed to allow somewhat leaner operation. Figures 3-17 through 3-20 compare sequential injection results with the group injection results at an air/fuel of 21.5:1 for various ignition timings. It can be seen that NO_x emissions are higher with sequential injection than with group injection when group injection results are compared with MBT results. MBT in this case was 40 degrees BTDC which is 3 degrees further advanced than the standard timing with group injection. This would result in somewhat higher NO_x with sequention injection; however, it is suspected that most of the increase is caused by the high energy, long duration spark. The increase in HC emissions could be the result of detonation caused by the high energy spark. The detonation problem is discussed in the next section.

From the sequential injection study, the following general conclusions and remarks can be made:

(1) At steady-state conditions and with the spray characteristics obtained from the Bendix fuel injectors, it is best to inject while the intake valve is closed. However, injecting into an open valve may not have a serious effect on emissions and performance at high engine rpm if a high energy spark is used.

(2) The changes in emissions and performance caused by different injection timings are more noticeable at relatively rich air/fuel (18:1 and 20:1) and ignition timing near MBT.

(3) Since all the tests were run at steady-state on a warmed-up engine, the effect of injection timings is not known for transient conditions such as acceleration, warm-up and cold start.

(4) Standard group injection timing essentially gives results as good as the best sequential injection timing "A".

(5) Although sequential injection timing"A" was selected initially as the best injection timing, "C" may give the least amount of CO and HC emissions at a cost of somewhat higher NO_x emissions and may extend the lean limit the farthest.

3.4 SPARK ENERGY/DURATION AND GAP SIZE

With ultra-lean mixtures in a combustion chamber, it is extremely difficult to sustain the combustion flame to obtain complete combustion. It was expected that increasing the spark plug gap, spark energy and the spark duration from the standard values would help achieve the combustion of the leaner air-fuel mixtures that are necessary to reduce NO_x emissions.

In general, the air-fuel mixture in a combustion chamber is non-homogeneous in that the mixture will be composed of very lean pockets, relatively rich pockets and even some inert pockets composed of residual exhaust.

The probability of igniting a relatively rich mixture to start the combustion would increase with increased spark gap size and a longer duration spark. Also the higher energy spark would reduce quenching by the electrodes and would even start combustion of those lean mixture pockets which would otherwise be difficult to ignite.(1)

A special ignition system was developed and fabricated to enable variation of spark energy and duration. Conventional ignition system components were used thereby providing easy installation. The basic principle of this ignition system was capacitor discharge with the added capability of multiple discharges for each ignition period.

Before evaluating ignition effects, since it is rather difficult to measure ignition energy on the engine, the various energy and duration levels were measured on the bench. Control settings for various energy levels and waveforms were noted and used later to perform tests on the engine.

Appendix D describes the test equipment and method used to measure spark energy and duration. It was recognized that spark duration and energy cannot be varied independently since once the gap was ionized, only so much energy could flow. Therefore, to vary energy, essentially, the duration was varied.

First, the control settings were obtained to simulate standard ignition energy level and duration. Figure D-16 in Appendix D shows standard spark energy and duration simulated by the special ignition system. Tests were run at these settings to make certain that using the special ignition system did not affect the engine performance or the emissions.

Two additional spark duration/energy settings were selected for the tests and are identified as No. 2 and No.3 energy/duration.

Control settings described in Figure D-18 (Appendix D) were used for the No. 2 energy/duration, except that four pulses were used which gave a spark energy of 80 millijoules and a duration of 2.8 milliseconds. Figure 3-21 shows current and voltage waveforms as seen on the operating engine.

Control settings described in Figure D-23 in Appendix D were used for energy/duration No. 3 except that 100 volts primary voltage and seven pulses were used. This resulted in 5.3 millisecond duration and 140 millijoules spark energy. Figure 3-22 shows current and voltage waveforms as observed on the operating engine.

Control settings described in Figure D-17 (Appendix D) were used for 0.045-inch and 0.060-inch spark plug gaps.

Table 3-2 summarizes the various ignition parameters used for this test.

To perform the tests, the injection timing was set at 45 degrees BTDC (intake) and tests were run for 1200 rpm, 45 b-ft-lbs; 1200 rpm, 100 b-ft-lbs and 640 rpm - 35 b-ft-bls (idle) set points. At each test point, ignition variables listed in Table 3-2 were varied, one at a time. For every ignition variable, ignition timing and air/fuel were varied. Air/fuel ratio was varied from 18:1 to the lean limit in increments of two air/fuel ratios. For idle ignition timings of 0 degree; 10 degrees and 20 degrees BTDC were used, and, for other test points ignition timings of MBT, 40 degrees, 25 degrees and 15 degrees BTDC were used.

Table 3-2 - Summary of Ignition Parameters

Ignition	Energy (millijoules)	Duration (milliseconds)	Gap (inches)
Standard	26.9	1.35	0.035
No. 2 Energy/Duration	80.0	2.8	0.035
No. 3 Energy/Duration	140.0	5.3	0.035
0.045-inch spark plug gap	28.8	1.48	0.045
0.060-inch spark plug gap	28.8	1.48	0.060

A problem was recognized when 5.3-millisecond duration spark was used at 1200 rpm. At this speed, and with retarded ignition timing, the contact time between the distributor rotor tip and the distributor cap is not sufficient to allow the 5.3-millisecond duration spark. The rotor was modified to have a much wider tip to increase the contact time with the distributor cap. It was anticipated that when performing tests at 2000 rpm, the contact time obtained with the standard rotor would not be sufficient for 2.8-millisecond spark duration and the use of the special rotor would be necessary. The modified rotor is shown in Figure 3-23.

Figures 3-24 and 3-25 show the effect of spark plug gap and spark duration on $BSNO_x$ and BSHC emissions for 1200 rpm, 45 b-ft-lbs test point. The air/fuel ratio was 20:1 and ignition timing 40 degrees BTDC. The complete set of data for this set point are listed in Appendix F, Section F.4 under "Ignition Effects".

From Figure 3-24 and 3-25, it can be seen that when the spark duration is increased from a standard value of 1.35 milliseconds to 2.8 milliseconds, BSHC decrease more than 22 percent and $BSNO_x$ decrease almost 30 percent.

It was mentioned earlier that the increased spark duration results in an increase in spark energy, prompting the anticipation of a decrease in HC emissions and an increase in NO_x emissions. The occurrence of exactly the opposite effect on NO_x emissions required some theorizing. A reduction of NO_x generally can be correlated with a lower concentration of O_2 and/or a lower peak cycle temperature. The air/fuel was maintained in this case so the reason for an apparent reduction in peak cycle temperature was sought. The purpose of an extended spark duration is to improve the probability of igniting the charge when it is so lean that ignitable pockets of fuel and air are relatively scarce. Thus, over a number of engine cycles, if the longer duration spark is successful in igniting the charge, it is probable that some charges ignite when the spark is first struck, others ignite just before the spark extinguishes and the rest ignite somewhere between the two extremes.

Probability theory would then suggest that the mean time of ignition of the charges is near the mid-point of the spark duration. At 2000 rpm with a 2.8 ms spark the crank angle rotation to the mid-point of spark duration (1.4 ms) is 8.4 degrees. This delay then is essentially the same as an equivalent spark retard of 8.4 degrees for which one normally expects lower peak temperatures and less NO_x.

Increasing the spark duration to 5.3 milliseconds decreased HC emissions further, but NO_x emissions increased. It seems that sufficient increase in spark energy has a significant effect on NO_x formation.

Trends were somewhat the same at different air/fuel and different ignition timings. However, small changes in NO_x emissions occurred with changes in spark duration for air/fuel leaner than 22:1 and for retarded ignition timings. On the other hand, large changes in HC emissions occurred with leaner air/fuel and retarded ignition timings.

Increasing the spark plug gap from the standard (0.035 inch) had a similar effect on HC and NO_x emissions as did increasing the duration. HC emissions decreased with increasing spark plug gap size. The wider gap allows more volume of the charge to be exposed to the spark between the electrodes, and thus it is believed that the combustion begins with a relatively large kernel of flame having more energy. This, in effect, could act like a higher energy spark. The results shown in Figures 3-24 and 3-25 reflect this argument.

Similar trends are observed at the 1200 rpm and 100 b-ft-lbs test point. Figures 3-26 and 3-27 show the effect of spark duration and spark plug gap at air/fuel of 20:1 and 40 degrees BTDC ignition timing. The slight increase in NO_x and HC emissions, when spark duration was changed from 1.35 milliseconds to 2.8 milliseconds, could be caused by experimental error in setting air/fuel and ignition timing. The decrease in HC emissions with increased spark plug gap and increased spark duration is small compared with that for the 45 b-ft-lbs torque set point. At 100 b-ft-lbs torque, the charge density is higher thus, during the compression stroke, the mixture is at higher temperature and pressure than at 45 b-ft-lbs torque and, even with the standard ignition system, better combustion is obtained. Therefore, relatively small gains are realized by increasing spark duration or spark plug gap at this test point.

Figures 3-28 and 3-29 show the effect of spark plug gap and spark duration on NO_x and HC emissions, respectively, at idle. The air/fuel is 12:1 and the ignition timing is 10 degrees BTDC. The NO_x emissions are reduced considerably by increasing either the spark plug gap or the spark duration and at the same time the HC emissions are increased. Apparently, increasing spark plug gap size and spark duration increases the tendency of misfire at idle.

From the test results obtained at the power set points discussed above, 0.045-inch spark plug gap and 2.8-millisecond spark duration with 80 millijoules of spark energy were selected to continue further tests with heated air to obtain "best parameter" combination results. Also, the above spark plug gap size and spark duration were used to evaluate effects of intake valve throttling.

As mentioned in Section 3.3, the above selected ignition parameters were used with 2000 rpm, 70 b-ft-lbs and 2000 rpm, 180 b-ft-lbs torque test points to re-evaluate sequential injection timings. A peculiar problem was experienced during these tests. Indolene clear (non-leaded) fuel was used to this point in the tests. However, with the higher energy and longer duration spark, a severe detonation problem was experienced with the 180 b-ft-lbs torque set point. It was postulated that with the high energy and long duration spark, flame fronts would start at several points around the spark plug electrodes, and these flame fronts would cause detonation. It was decided to use a higher octane fuel for these test points so Indolene 30 was selected. Indolene clear has a research octane of 98 (motor octane of 92) and Indolene 30 has a research octane of 105 and a motor octane of 100. Use of the higher octane fuel alleviated the detonation.

Reviewing Figures 3-24 through 3-29, one important conclusion could be made that the increase in either the spark gap or the spark duration and energy have similar effects on both the NO_x and HC emissions. Thus, by merely widening the spark plug gap and making certain that the ignition system would provide enough energy to strike the spark across the gap, results similar to that obtained with longer duration and higher energy spark could be obtained.

3.5 INLET AIR HEATING

Increasing the temperature of the intake air could help vaporize the fuel which would provide a more homogeneous mixture of the air and the fuel. As a result, chances of complete combustion would increase. Better combustion would allow leaner operation, resulting in reduction of NO_x; however, at a given air/fuel ratio increased inlet air temperature may increase NO_x emissions. Also, the decrease in the density of the inlet air would decrease the volumetric efficiency of the engine. The inlet air temperature for these tests was limited to a maximum of 200°F to ensure sufficient power at the maximum air flow conditions.

To heat the inlet air, a duct-type finned air heater was procured with a heating capacity of 12 kilowatts. A temperature controller was employed to set and maintain the inlet air temperature at a desired value. The controller maintained the temperature within ±5°F of the set point. The inlet air heating installation is shown in Figure 3-30.

The inlet air heating tests were conducted for all five selected test points. The best ignition parameters and the best sequential injection timing selected earlier were used and three inlet air temperatures, namely, 100°, 150° and 200°F, were used. It also was intended to find the "best" parameter combination from these tests. The "best" parameters would consist of the best inlet air temperature, the best injection timing, and the best ignition parameters that would allow ultra-lean operation, resulting in a decrease of NO_x emissions.

To perform the tests, the sequential injection timing was 45 degrees BTDC (intake) , the spark plug gap was 0.045 inch and spark duration was 2.8 milliseconds with 80 millijoules spark energy. For each engine speed and torque, the inlet air temperature was set and air/fuel ratio and ignition timing were varied. The MBT ignition timing was found for each temperature.

Figures 3-31 through 3-40 show the effect of inlet air temperature on $BSNO_x$ and BSHC emissions for all the selected power set points at certain air/fuel and ignition timings as indicated on the respective figures. The complete set of data obtained are listed in Appendix F under "Inlet Air Heating". The trends shown in Figures 3-31 through 3-40 are typical of all the air/fuel and ignition timings. However, the change in NO_x emissions is not significant when inlet air temperature is changed at very lean air/fuel and with retarded timings.

As expected, increasing the inlet air temperature increases NO_x and decreases HC emissions. At 2000 rpm, increase in the inlet air temperature does not significantly reduce HC emissions. Again, at such engine speed, the increased turbulence in the combustion chamber affects the combustion more than anything else. The problem of severe detonation was observed for air temperatures of 150°F and 200°F at the 200 rpm and

180 b-ft-lbs power set point. Besides the use Indolene-30 fuel, it became necessary to use standard spark energy, duration and spark plug gap to solve the detonation problem. The problem was not solved, however, at all the air/fuel and ignition timings and this resulted in limited data for this test point.

Since these tests were performed with the "best" injection timing and the "best" ignition parameters, it was intended to find a "best" parameter combination for each power set point which resulted in minimum NO_x emissions. The best parameter combination, obviously, depends on the kinds of trade-offs that are acceptable. Since the goal of this project was to reduce NO_x, very little consideration was given to either the fuel economy or the HC and CO emissions. The "best" parameter combination consisted of selecting, for a given speed and torque, the air/fuel the ignition timing, and the inlet air temperature from the tabulated data in Appendix F for the minimum NO_x emission. Table 3-3 summarizes the results. Also, the baseline results are shown for comparison. As noted previously, the "best" parameter combination used injection timing of 45 degrees BTDC (intake) along with spark plug gap of 0.045 inch and spark duration of 2.8 milliseconds with 80 millijoules spark energy.

With the "best" parameter combination, a minimum of 59 percent to a maximum of 84 percent reduction in the $BSNO_x$ was realized, referenced to the baseline EFI tests. Except for the 2000 rpm test points, a decrease in the BSFC and a decrease in the BSCO emission were realized and except for idle, the BSHC emission increased substantially.

3.6 INTAKE VALVE THROTTLING (IVT)

In the conventional EFI fuel management system, the air is throttled at the throttle body in a manner similar to a carburetor. Thus, a major pressure drop occurs at the throttle plates and there is very little pressure drop across the intake valve. If the pressure drop could occur across the intake valve instead, considerable turbulence would be created inside the combustion chamber.

It has been shown that with such turbulence, satisfactory spark ignition engine operation could be obtained with extremely lean mixture ratios at very light loads. (3) It was envisioned that better combustion and faster travel of the flame front resulting from IVT would, for a given air/fuel decrease HC emissions, but would increase the NO_x emissions. However, it was hoped that the resulting lean-limit extension would allow engine operation at ultra-lean mixtures and the resulting NO_x trade-off would be favorable.

To limit the lift of the intake valve, three specially ground camshafts were used. The valve timing and the opening and closing ramps were not altered. The intake valve lobes were ground to lower lifts to correspond to the following mass air flows:

Table 3-3 - Summary of the Baseline and the Best Parameter Results

rpm	Torque b-ft-lbs	Test	Ignition Timing °BTDC	A/F	Inlet Air Temp. °F	BSFC lbs/b-hp-hr	$BSNO_x$	BSCO	BSHC
							gm/b-hp-hr		
640	35	Baseline Best Parameter	6 0	13.6 18:1	80 150	1.45 1.33	1.3 0.22	131.2 14.7	8.2 10.0
1200	45	Baseline Best Parameter	12 15	21:1 22:1	77 150	1.41 0.96	0.89 0.36	25.2 15.4	4.7 10.1
1200	100	Baseline Best Parameter	13 25	21.4:1 24:1	76 200	0.77 0.63	0.59 0.23	70.55 7.5	2.85 28.2
2000	70	Baseline Best Parameter	37 25	21.8:1 24:1	79 200	0.8 0.86	1.49 0.32	7.99 16.6	3.61 47.2
2000	180	Baseline Best Parameter	37 25	21.5:1 22.6:1	82 100	0.48 0.54	2.4 0.81	9.65 9.96	0.69 12.5

P85 436 2

A - $100 \frac{\text{lbs}}{\text{hr}}$ at 640 rpm

B - $400 \frac{\text{lbs}}{\text{hr}}$ at 1200 rpm

C - $800 \frac{\text{lbs}}{\text{hr}}$ at 2000 rpm

It was assumed that camshafts A, B and C would provide the maximum air flows required at idle; 1200 rpm, 100 b-ft-lbs and 2000 rpm, 180 b-ft-lbs set points, respectively. It was decided that to run tests at 1200 rpm, 45 b-ft-lbs and 2000 rpm, 70 b-ft-lbs, the throttle would be used along with camshafts B and C, respectively.

After installing camshaft A, it was discovered that maximum air flow obtained at idle was not sufficient to allow engine operation at an air/fuel leaner than 14.6:1. It was decided to use camshaft B at idle to obtain air/fuel up to 22:1. Camshaft B was also used for the 2000 rpm, 70 b-ft-lbs set point to minimize the pressure drop at the throttle to achieve the desired air flows. Thus, camshaft C was used for the 2000 rpm, 180 b-ft-lbs set point; and for all the other set points, camshaft B was used.

To perform the tests, a sequential injection timing of 45 degrees BTDC (intake), a spark plug gap of 0.045 inch, and a spark duration of 2.8 milliseconds with 80 millijoules spark energy were used. With each camshaft installed, for the given engine speed and torque, A/F and ignition timing were varied. The MBT spark timing was found for each test point. The obtained data are tabulated in Appendix F under "Intake Valve Throttling", p. F-33.

One very important observation was made. Except for the 1200 rpm, 100 b-ft-lbs torque set point, the MBT ignition timings for the other three set points were retarded considerably more than normal. Increasing the mixture turbulence in a combustion chamber is known to increase the speed of the flame propagation.(4) The increased flame propagation increases the rate of the cylinder pressure rise and, possibly, also the peak cylinder temperature. Evidently, the faster rate of the cylinder pressure rise results in MBT timing close to TDC. Detonation at certain test conditions with the high load and relatively high A/F was found to be a problem. Again, the fast rise in the cylinder pressure, along with the high energy spark, could be the cause of this. Data were not taken at such test conditions.

When compared with the results obtained earlier, except for the 2000 rpm, 180 b-ft-lbs power point, for a given air/fuel and the ignition timing, the $BSNO_x$ emissions were higher, the BSFC and BSCO were lower, and the BSHC emissions were higher with intake valve throttling. For the 2000 rpm, 180 b-ft-lbs power set point, the BSHC emissions were lower too when compared with the results obtained previously with the other parameters.

From the obtained data, by selecting A/F and ignition timing for the least NO_x emissions, a best-parameter combination can be obtained with the IVT. Table 3-4 summarizes the results. Comparing the results with the best parameter combination in Table 3-3, it can be seen that IVT produces much higher $BSNO_x$ even with the leaner mixtures in some cases. Marked improvement in BSFC is realized for both 2000 rpm set points. Reduction in BSCO is significant in all cases, however, except for the 2000 rpm, 180 b-ft-lbs set point, BSHC emissions increase. The increase in BSHC emissions was contradictory to what was expected. It is believed that this might have occurred because of the uneven distribution of the air/fuel among the cylinders. Since, with IVT, the metering of the intake air is accomplished at the intake valve, the individual lift of the intake valve determines the air flow. The variation in lift from valve to valve could affect the air flow distribution and hence the air/fuel. Thus, at a given average A/F some cylinders may be running leaner than the others and causing misfire. Although this might have limited the extension of the lean limit, it is felt from the trends in the $BSNO_x$ emissions that with IVT, even with leaner A/F, the $BSNO_x$ emissions would not be as low as that obtained with heated intake air.

Table 3-4 - Summary of the Best Parameter Results with the Intake Valve Throttling

Engine Speed rpm	Torque b-ft-lbs	Ignition Timing °BTDC	A/F	BSFC	BSNO$_x$	BSCO	BSHC
				lb/b-hp-hr	gm/b-hp-hr		
640	35	0	20:1	1.5	0.56	11.0	17.0
1200	45	20 (MBT)	22:1	0.9	0.45	9.7	43.2
1200	100	40 (MBT)	23.4:1	0.6	0.41	4.6	34.0
2000	70	15	22:1	0.7	1.60	9.8	18.7
2000	180	30 (MBT)	24:1	0.44	1.26	3.6	5.8

P-85-436-2

3.7 TEST RESULTS CORRELATION

A plot was constructed with some of the data obtained during this investigation and with other data obtained previously during an investigation conducted by the Bendix Research Laboratories. The purpose was to determine the correlation between the two test programs since the previous Bendix test used a 9:1 C. R. version of the same engine. In addition, the data obtained during the subject investigation are for a regime of air-fuel ratios not previously explored in depth (18:1 and higher) as compared to the usual carburetor air-fuel ratios. Thus, these data can help to establish the trends of NO$_x$, CO and HC emissions at very lean A/F.

Figure 3-41 shows the results of the plot. All data are for MBT spark timing of 40° BTDC, but those data for air-fuel ratios of 18:1 and higher were obtained during the subject program and are for 100°F inlet air, a spark plug gap of 0.045 inch and a spark duration of 2.8 ms. The data for the lower air-fuel ratios are for standard spark duration and plug gap.

The bands of data include power set points of 1200 rpm at 45, 75 and 100 brake ft-lbs torque and 2000 rpm at 70 brake ft-lbs torque. The specific curves shown are for 1200 rpm at 45 brake ft-lbs torque. The specific curves help to show how well the two sets of data correlate even though the compression ratios were different.

The "best" parameter emissions data at an A/F of 22:1 for 1200 rpm at 45 brake ft-lbs torque are also shown.

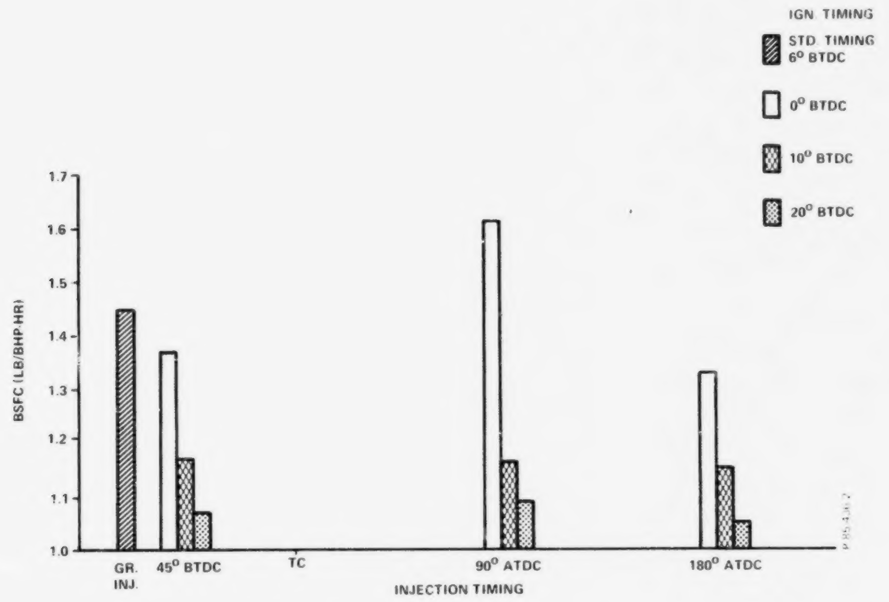

Figure 3-1 - Effect of Injection Timing on BSFC, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6

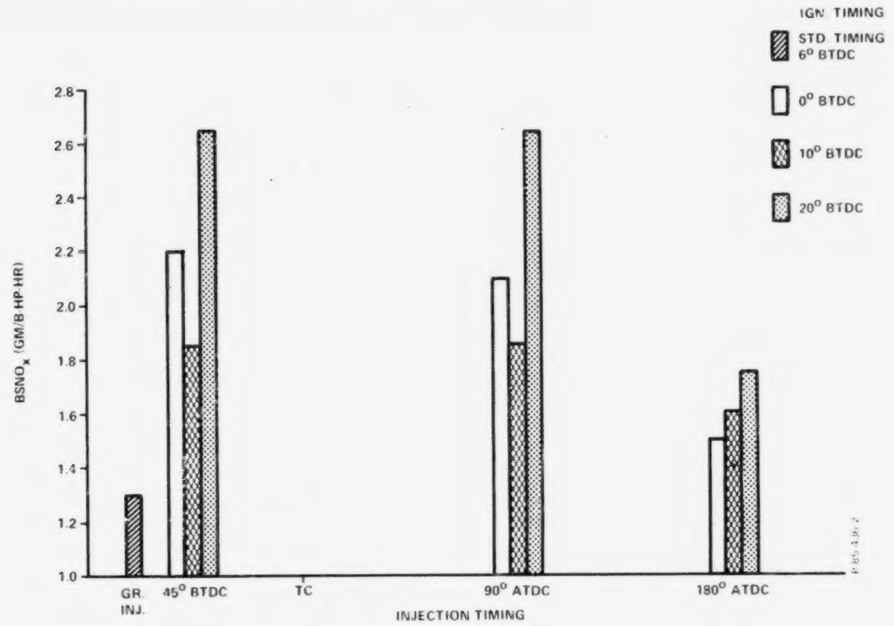

Figure 3-2 - Effect of Injection Timing on BSNO$_x$, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6

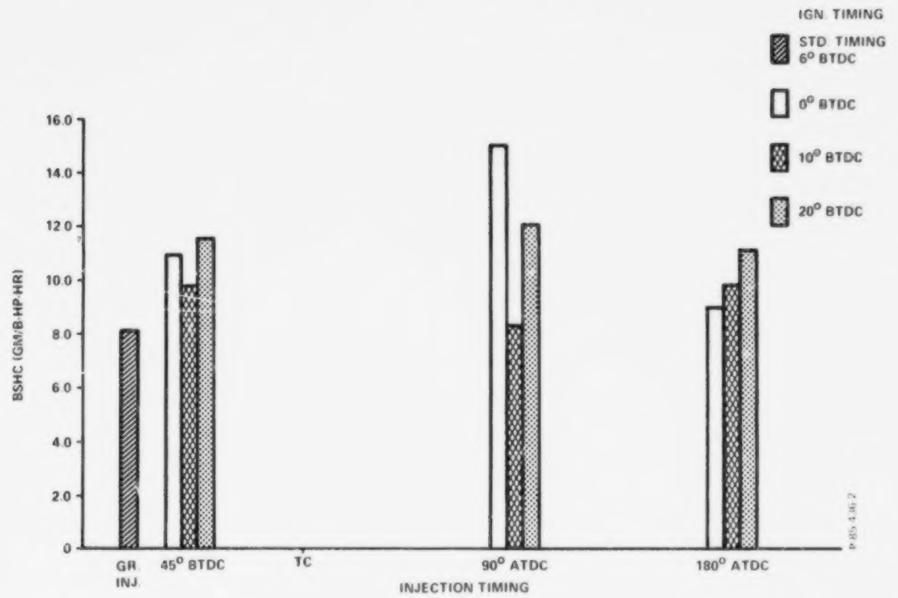

Figure 3-3 - Effect of Injection Timing on BSHC, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6

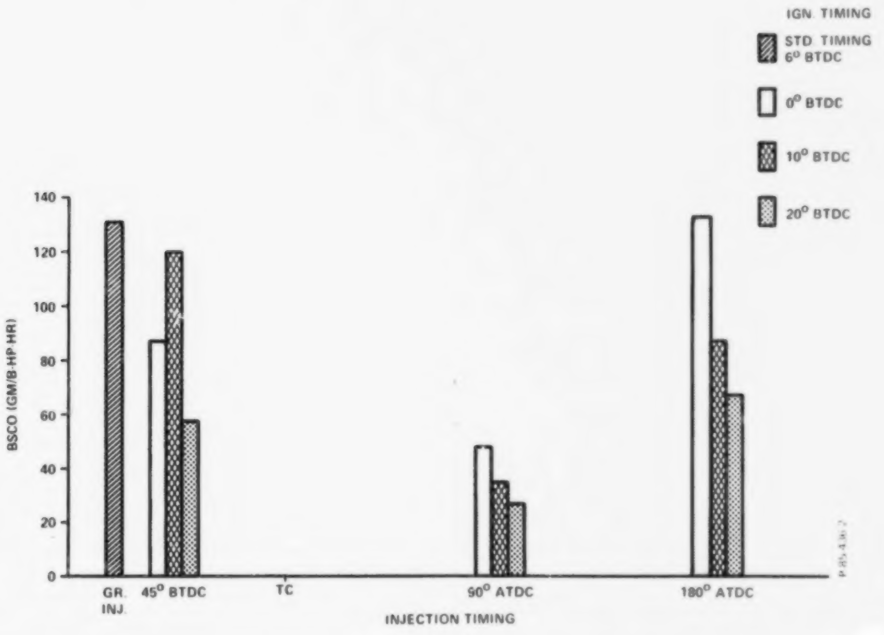

Figure 3-4 - Effect of Injection Timing on BSCO, 640 rpm - 35 b-ft-lbs, (Idle), A/F = 13.6

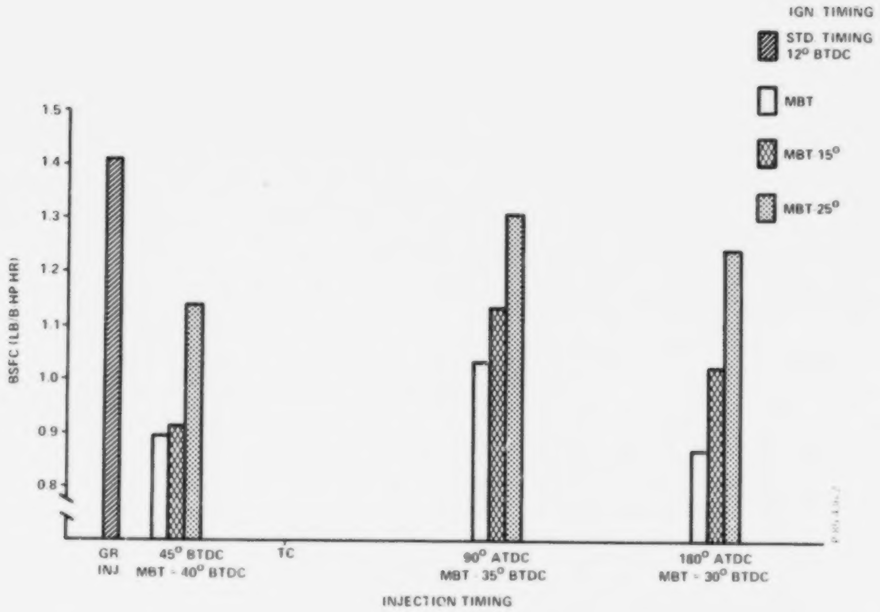

Figure 3-5 - Effect of Injection Timing on BSFC, 1200 rpm - 45 b-ft-lbs, A/F = 21:1

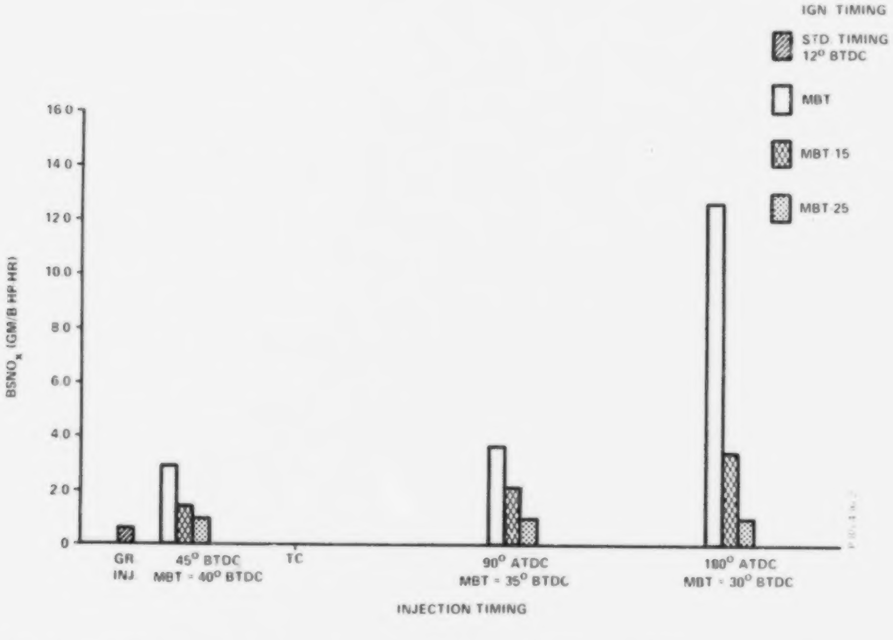

Figure 3-6 - Effect of Injection Timing on $BSNO_x$, 1200 rpm - 45 b-ft-lbs, A/F = 21:1

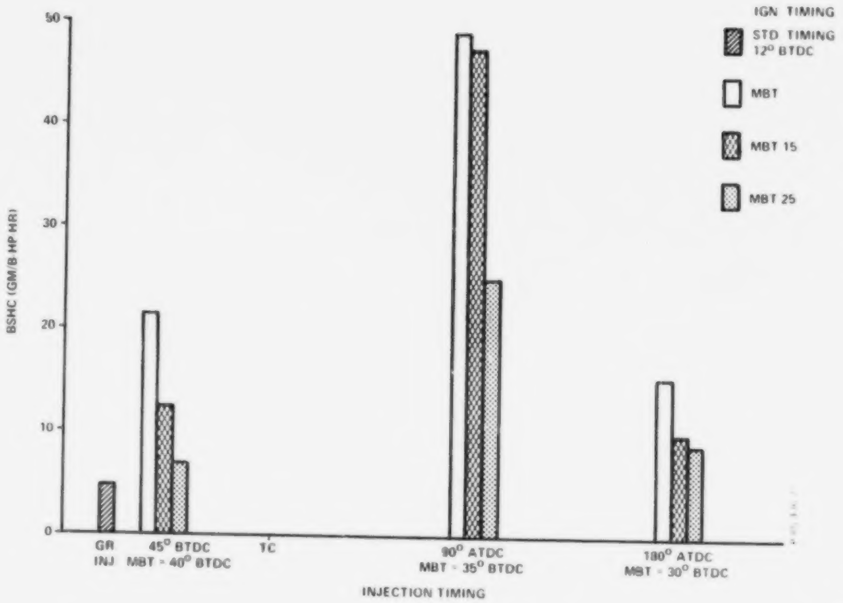

Figure 3-7 - Effect of Injection Timing on BSHC, 1200 rpm - 45 b-ft-lbs, A/F = 21:1

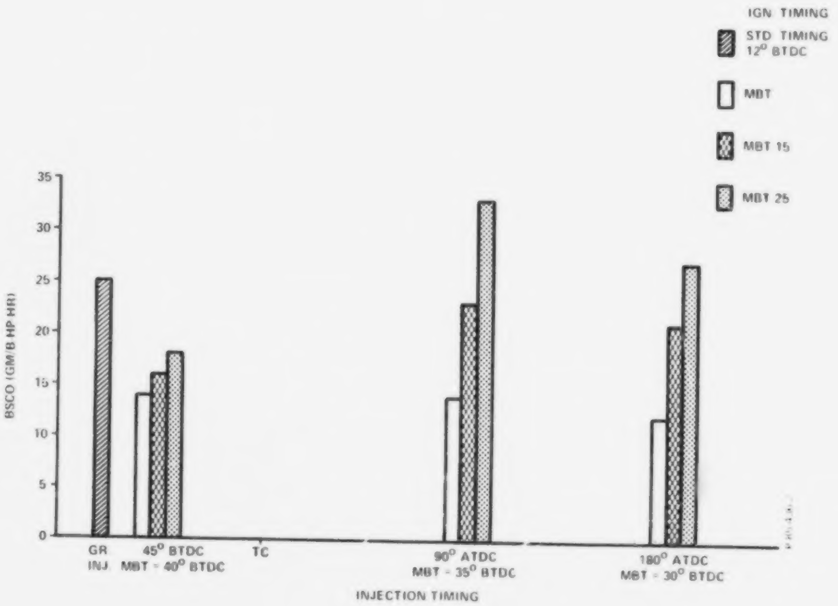

Figure 3-8 - Effect of Injection Timing on BSCO, 1200 rpm - 45 b-ft-lbs, A/F = 21:1

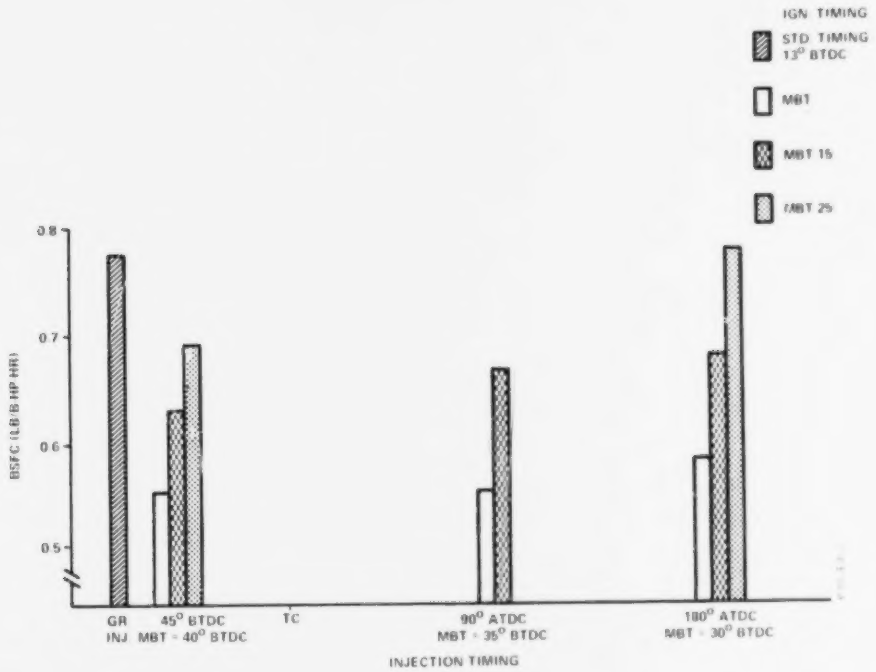

Figure 3-9 - Effect of Injection Timing on BSFC, 1200 rpm - 100 b-ft-lbs, A/F = 21.4

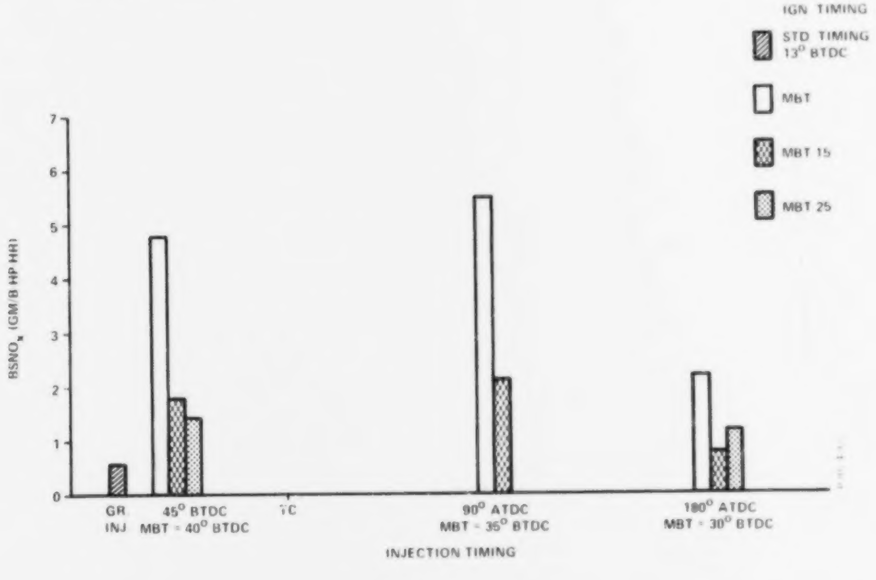

Figure 3-10 - Effect of Injection Timing on BSNO$_x$, 1200 rpm - 100 b-ft-lbs, A/F = 21.4

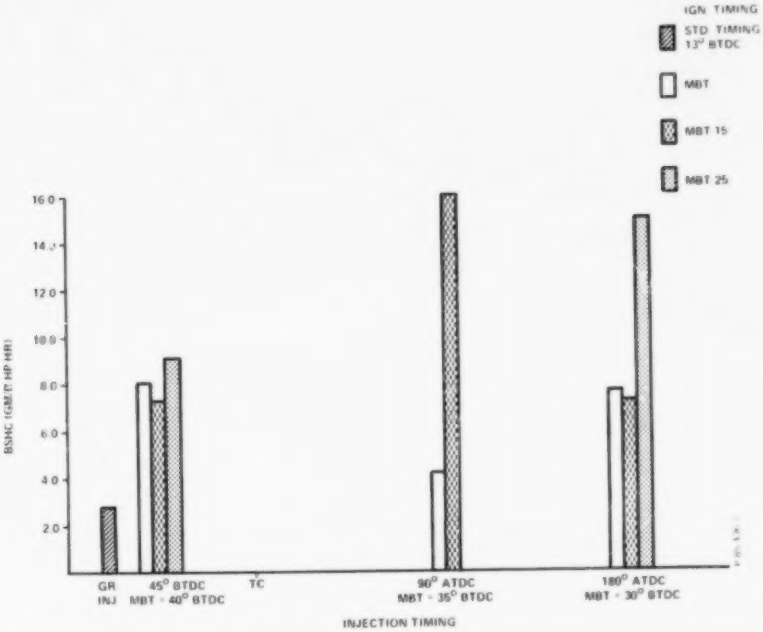

Figure 3-11 - Effect of Injection Timing on BSHC, 1200 rpm - 100 b-ft-lbs, A/F = 21.4

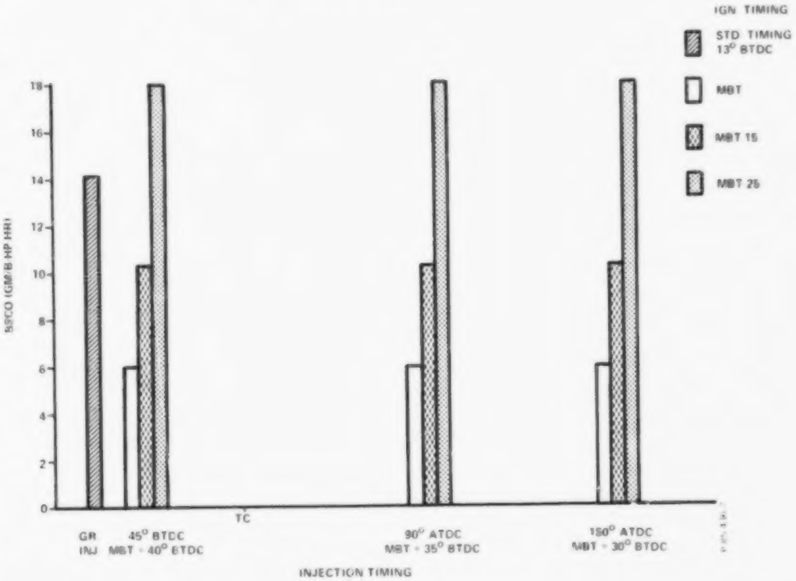

Figure 3-12 - Effect of Injection Timing on BSCO, 1200 rpm - 100 b-ft-lbs, A/F = 21.4

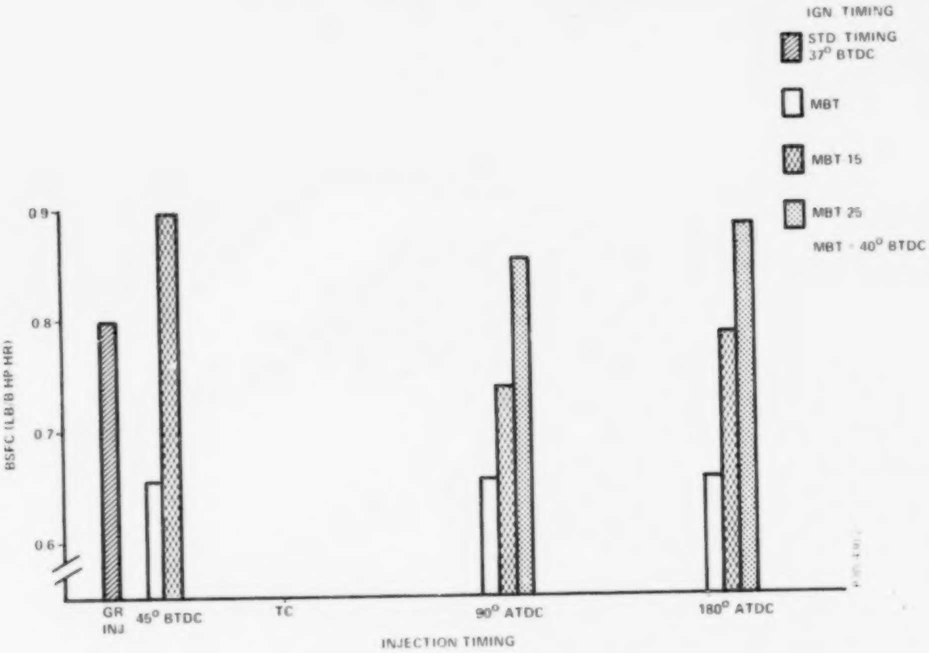

Figure 3-13 - Effect of Injection Timing on BSFC, 2000 rpm - 70 b-ft-lbs, A/F = 21.8

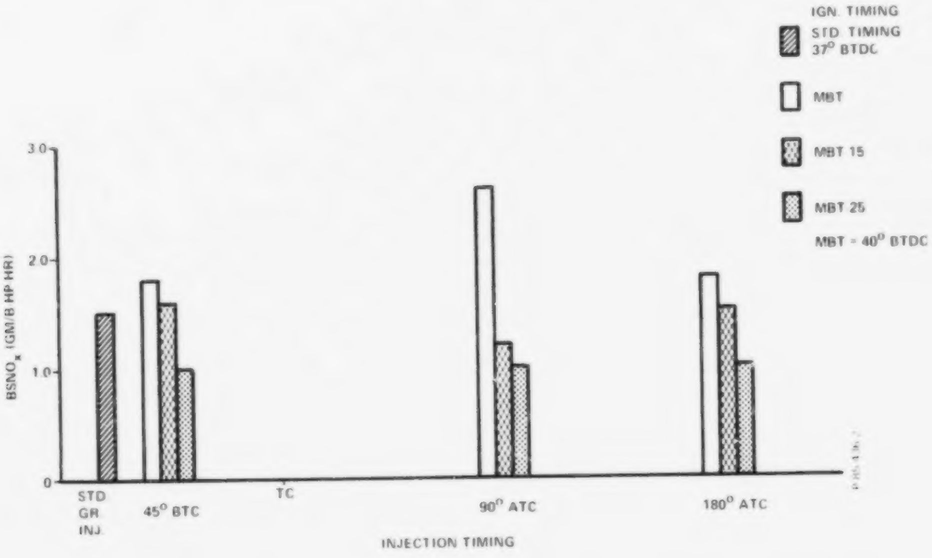

Figure 3-14 - Effect of Injection Timing on BSNO$_x$, 2000 rpm - 70 b-ft-lbs, A/F = 21.8

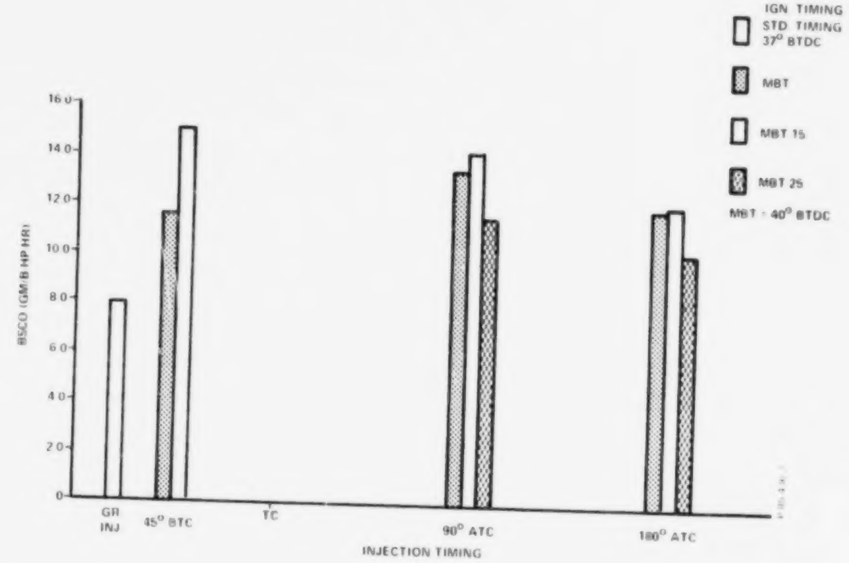

Figure 3-15 - Effect of Injection Timing on BSCO, 2000 rpm - 70 b-ft-lbs, A/F = 21.8

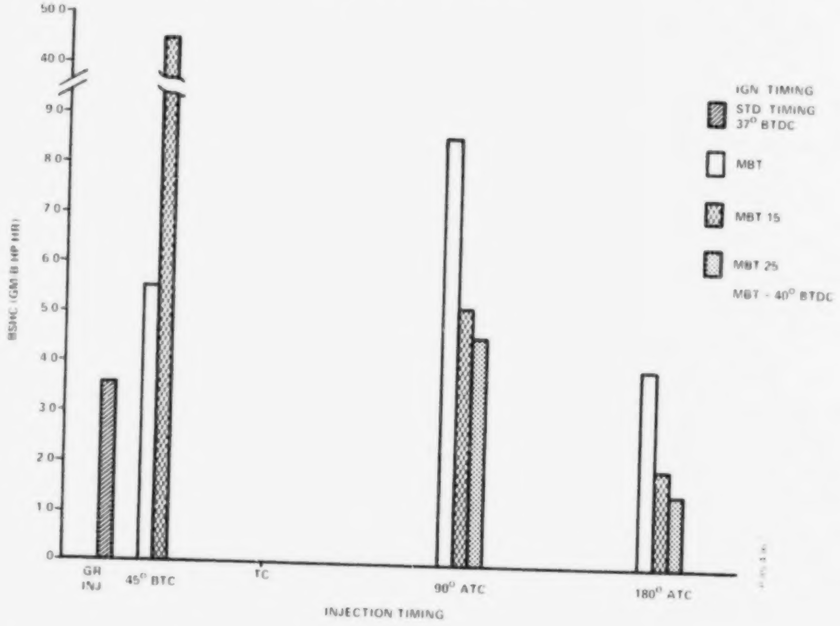

Figure 3-16 - Effect of Injection Timing on BSHC, 2000 rpm - 70 b-ft-lbs, A/F = 21.8

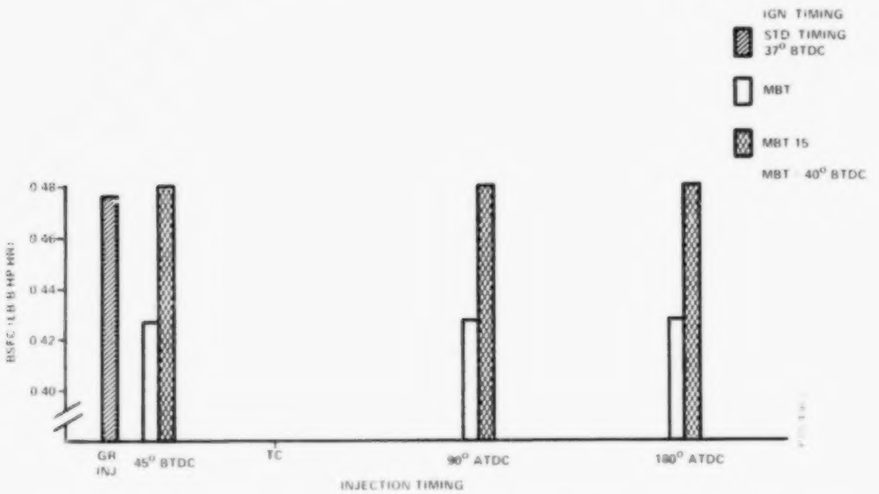

Figure 3-17 - Effect of Injection Timing on BSFC, 2000 rpm - 180 b-ft-lbs, A/F = 21.5

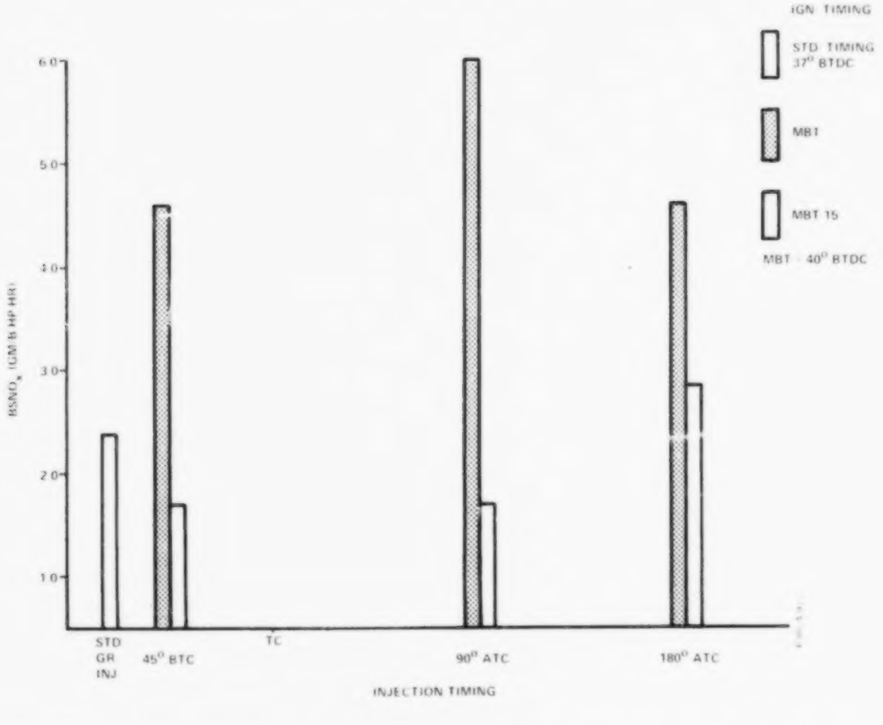

Figure 3-18 - Effect of Injection Timing on BSNO$_X$, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1

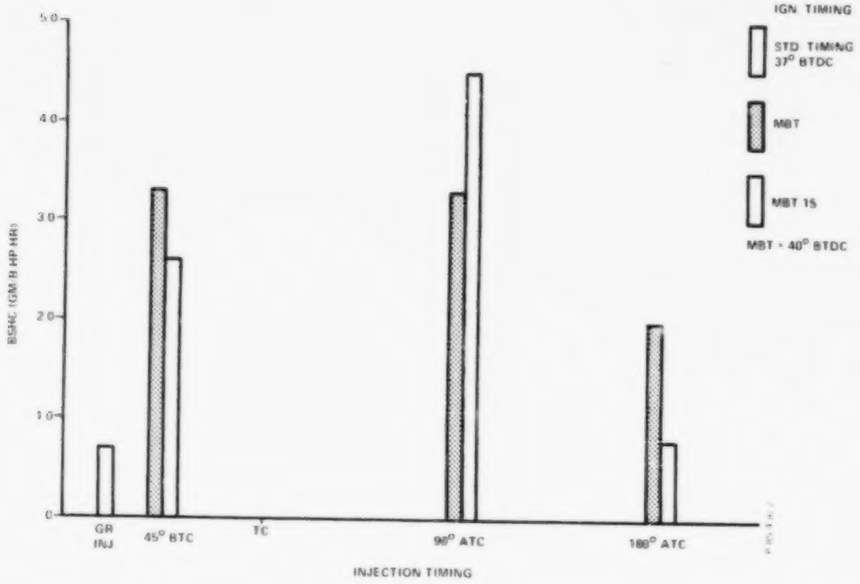

Figure 3-19 - Effect of Injection Timing on BSHC, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1

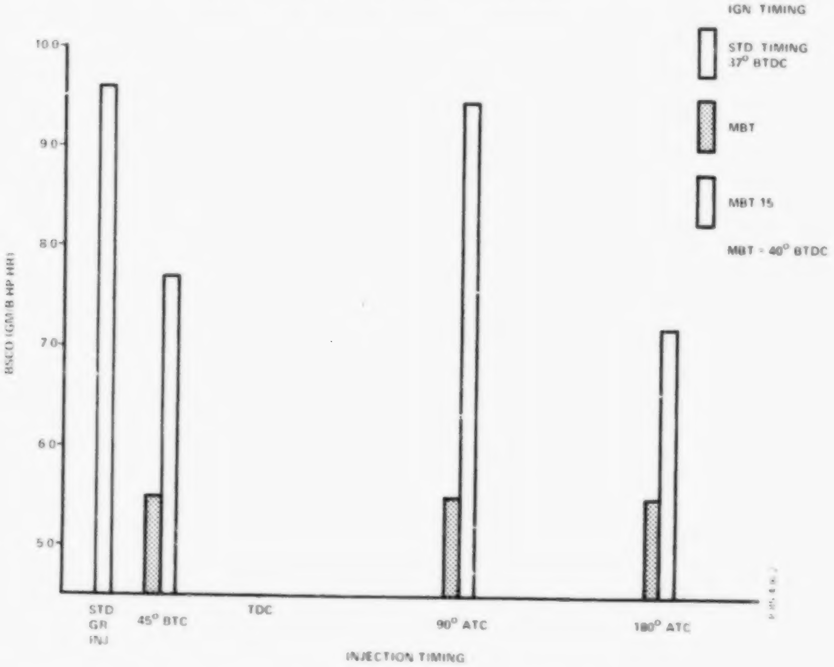

Figure 3-20 - Effect of Injection Timing on BSCO, 2000 rpm - 180 b-ft-lbs, A/F = 21.5:1

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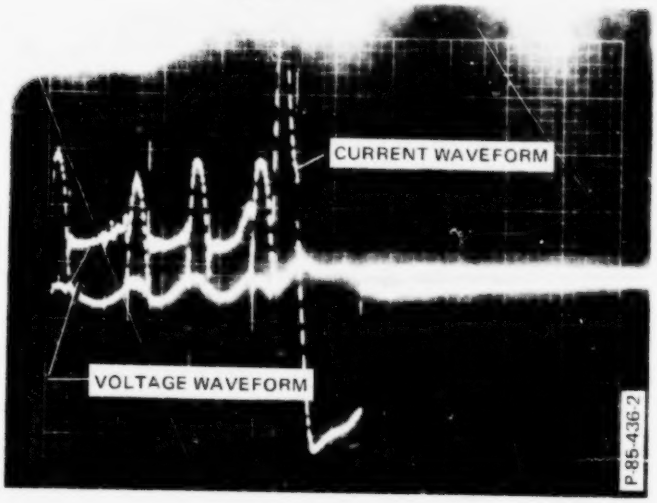

Figure 3-21 - Current and Voltage Waveforms for 2.8 Millisecond Duration and 80 Millijoules Energy Spark (Voltage = 1000 V/cm; Current = 0.05 A/cm; Time = 0.5 msec/cm)

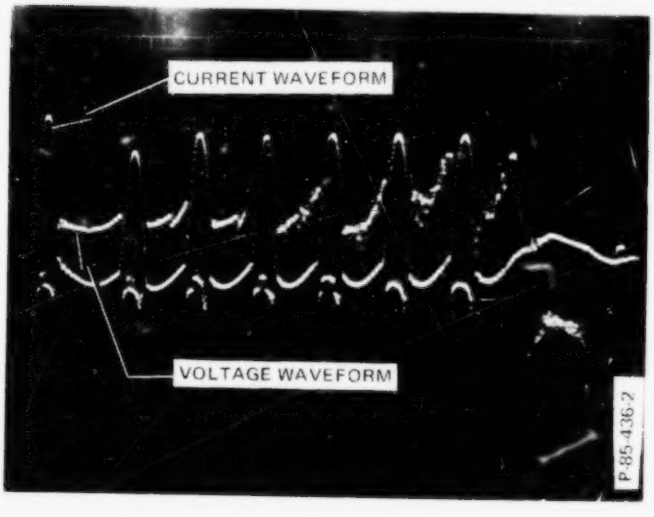

Figure 3-22 - Current and Voltage Waveforms for 5.3 Millisecond Duration and 140 Millijoules Energy Spark (Voltage = 1000 V/cm; Current = 0.05 A/cm; Time = 0.5 msec/cm)

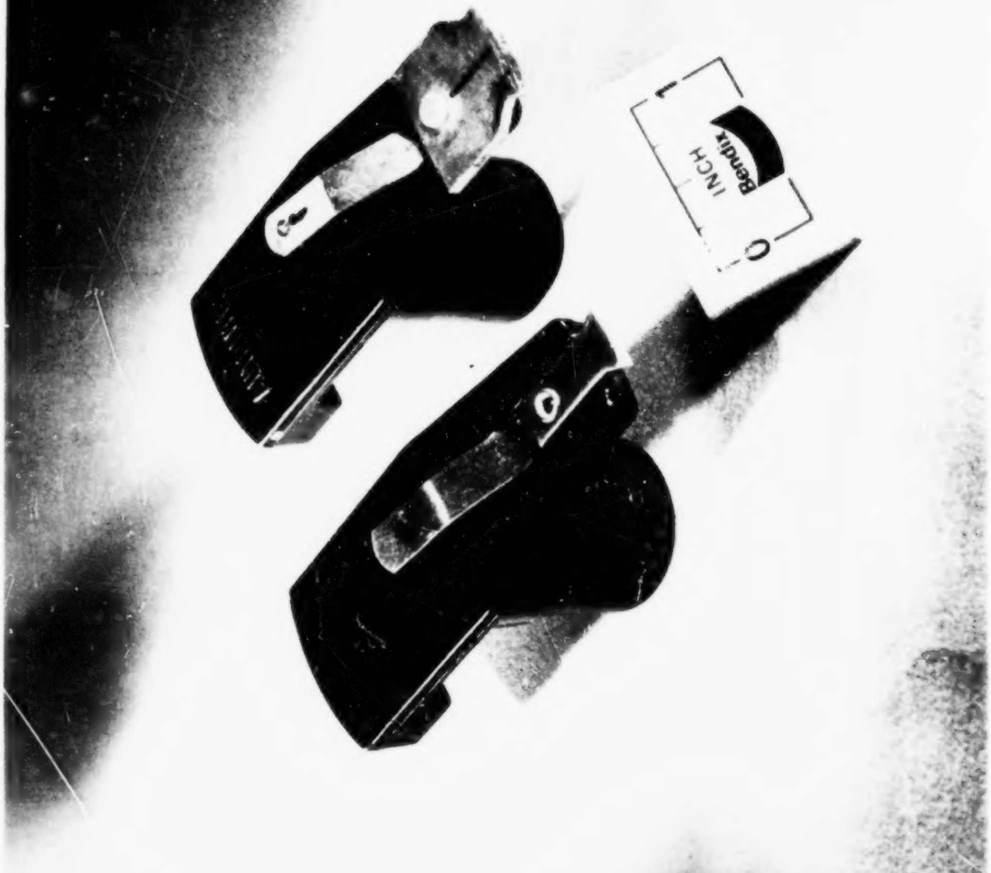
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Figure 3-23 - Modified Rotor

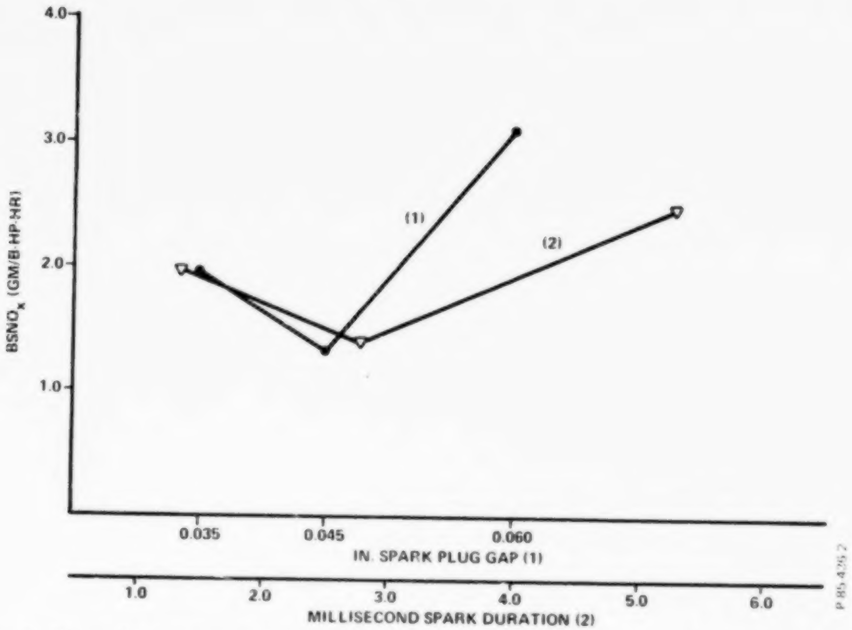

Figure 3-24 - Effect of Spark Plug Gap and Spark Duration/Energy on NO$_x$ Emissions, Engine Speed - 1200 rpm, Torque - 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

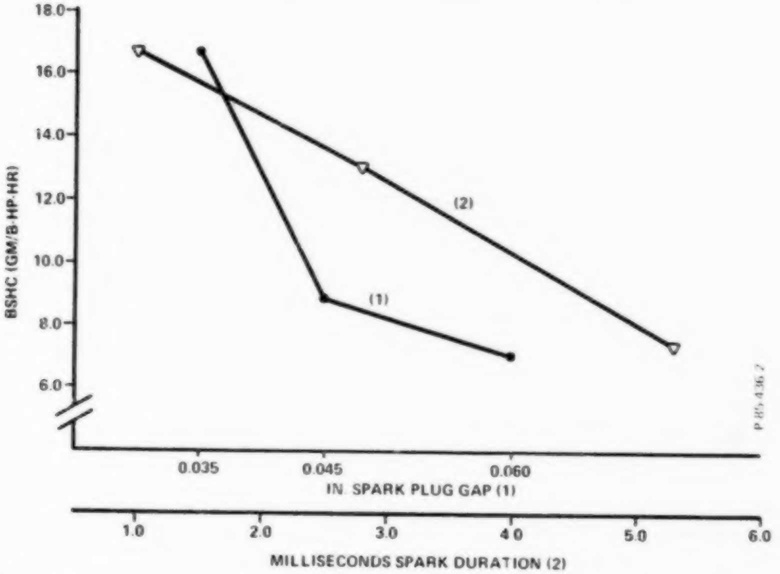

Figure 3-25 - Effect of Spark Gap and Duration/Energy on HC Emissions, Engine Speed - 1200 rpm, Torque - 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

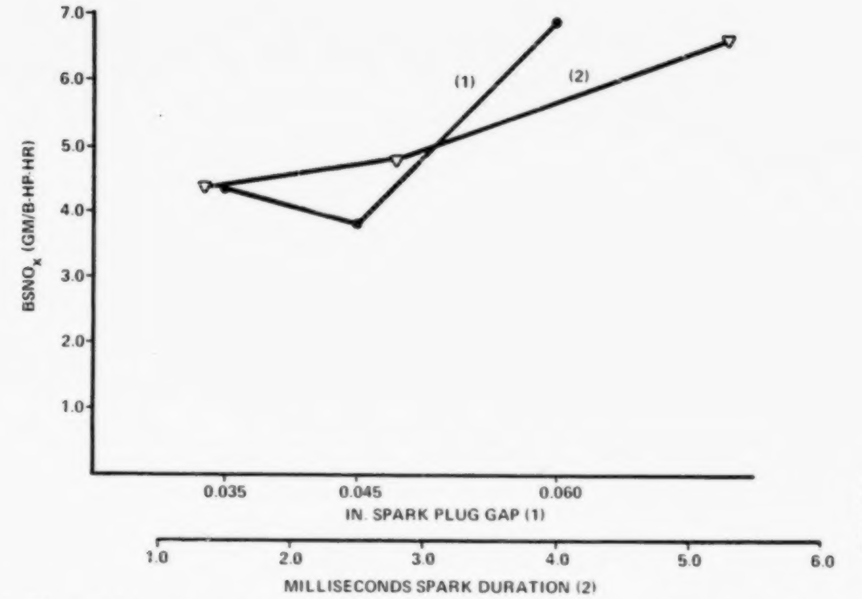

Figure 3-26 - Effect of Spark Plug Gap and Spark Duration on NO_x Emissions, Engine Speed - 1200 rpm, Torque - 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

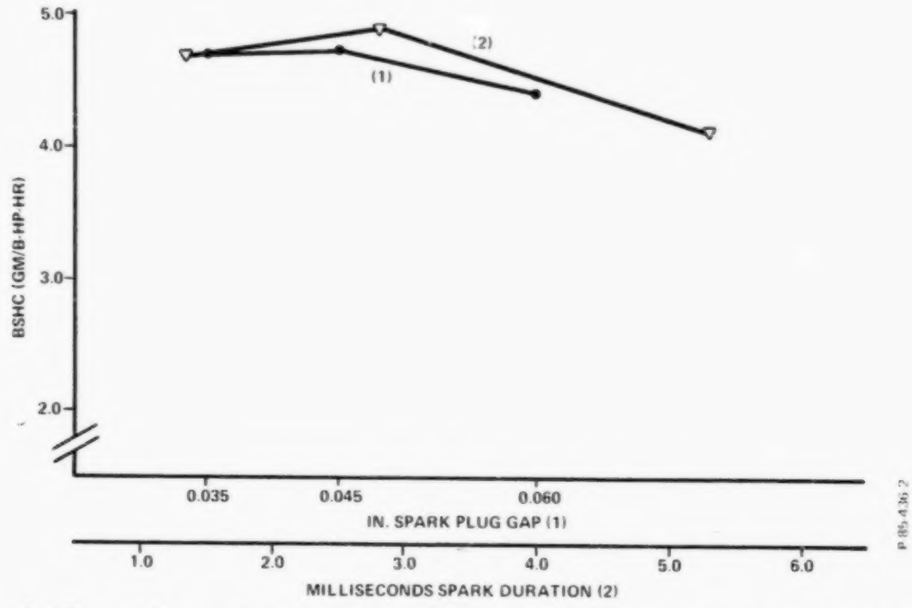

Figure 3-27 - Effect of Spark Plug Gap and Spark Duration on HC Emissions, Engine Speed - 1200 rpm, Torque - 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

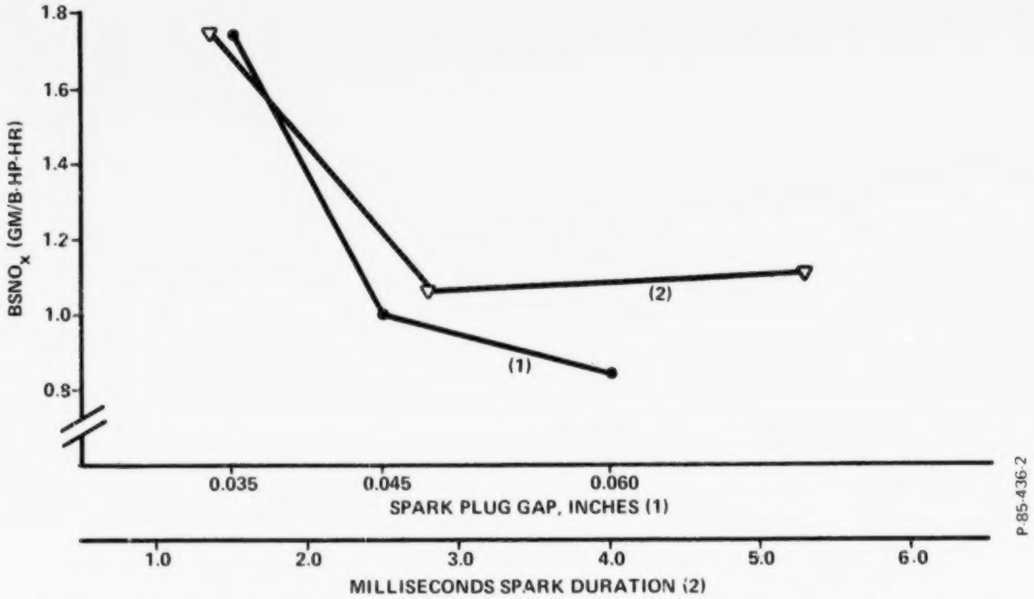

Figure 3-28 - Effect of Spark Plug Gap and Spark Duration on NO$_X$ Emissions, Engine Speed - 640 rpm, Torque - 35 b-ft-lbs (Idle), A/F = 12:1, Ignition Timing - 10° BTDC

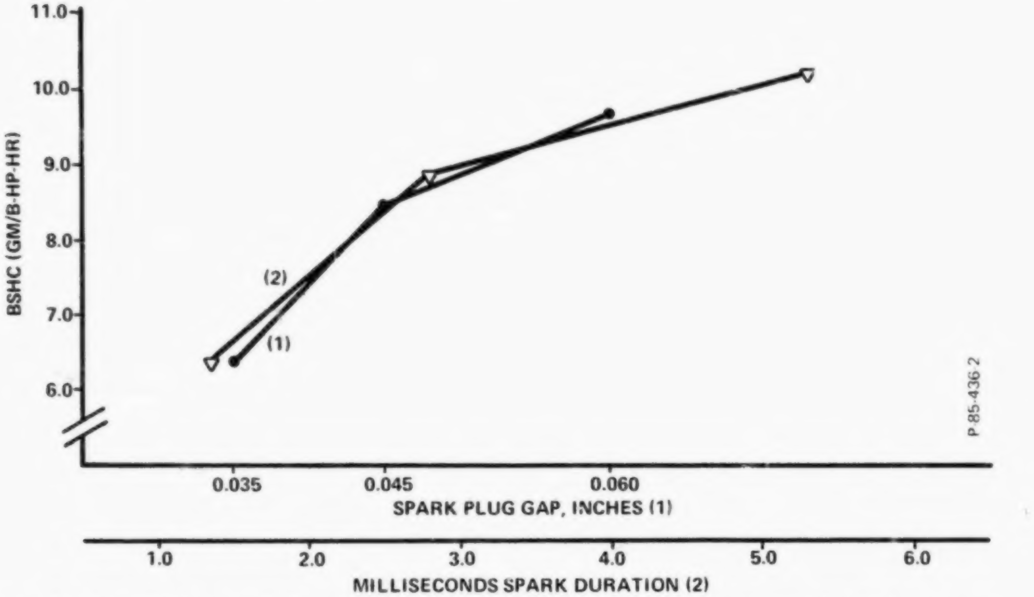

Figure 3-29 - Effect of Spark Plug Gap and Spark Duration on HC Emissions, Engine Speed - 640 rpm, Torque - 35 b-ft-lbs (Idle), A/F = 12:1, Ignition Timing - 10° BTDC

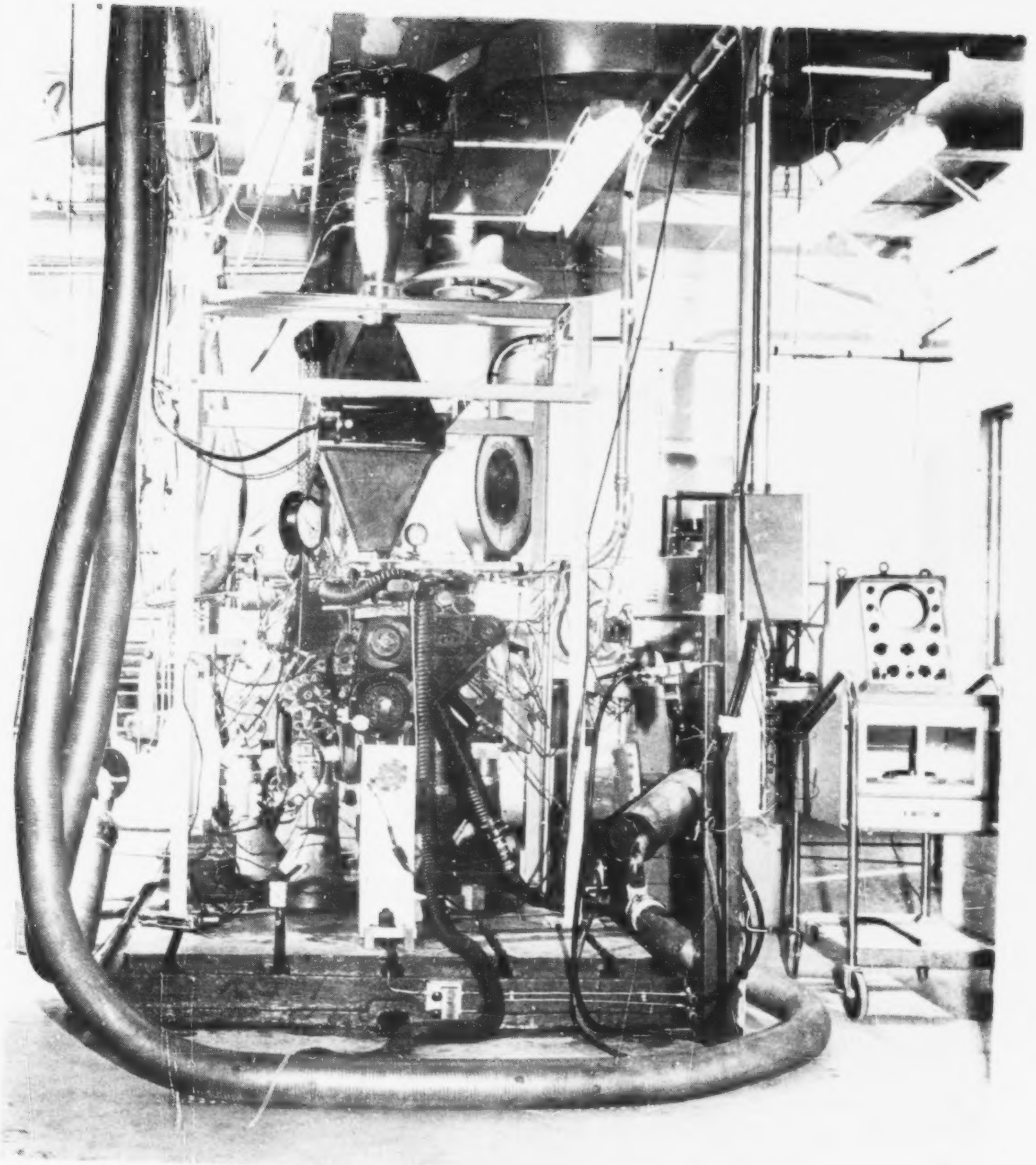

Figure 3-30 - Inlet Air Heating Test Set Up

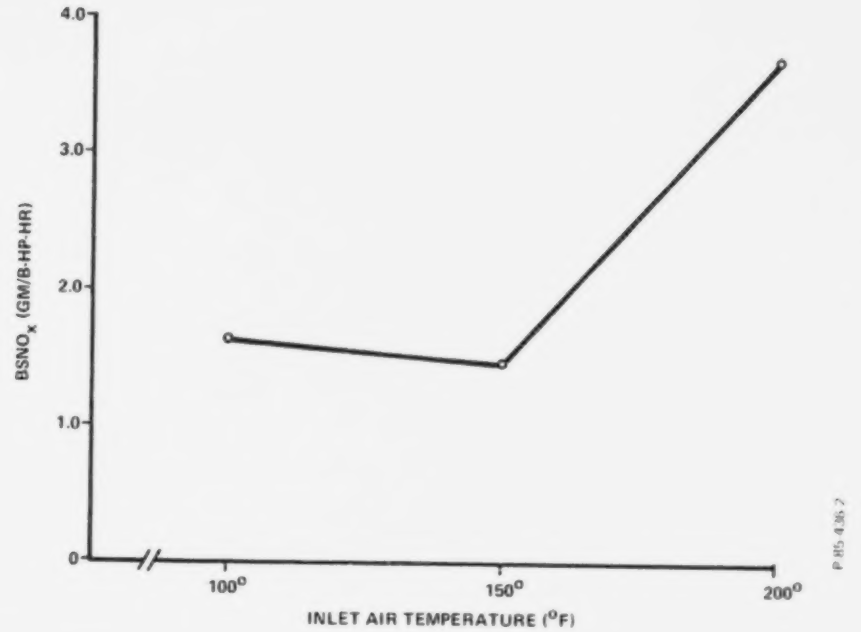

Figure 3-31 - Effect of Inlet Air Temperature on BSNO$_x$, 1200 rpm, 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

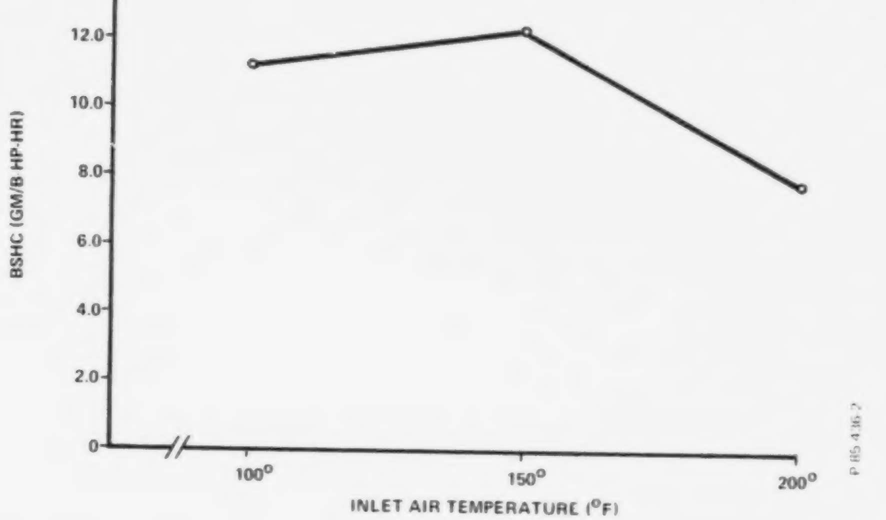

Figure 3-32 - Effect of Inlet Air Temperature on BSHC, 1200 rpm, 45 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

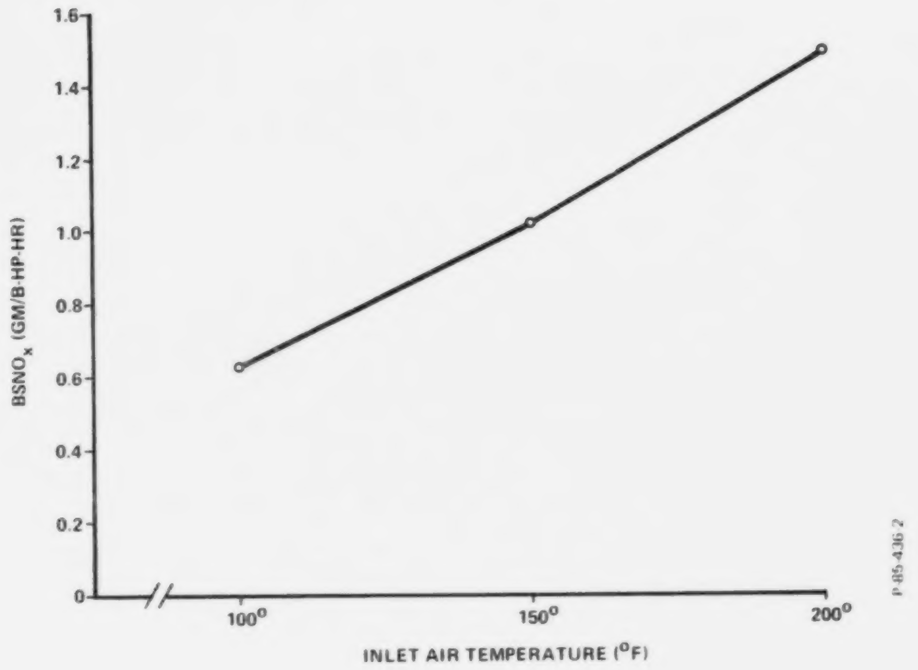

Figure 3-33 - Effect of Inlet Air Temperature on BSNO$_x$, 640 rpm, 35 b-ft-lbs (Idle), A/F = 13.9:1, Ignition Timing - 10° BTDC

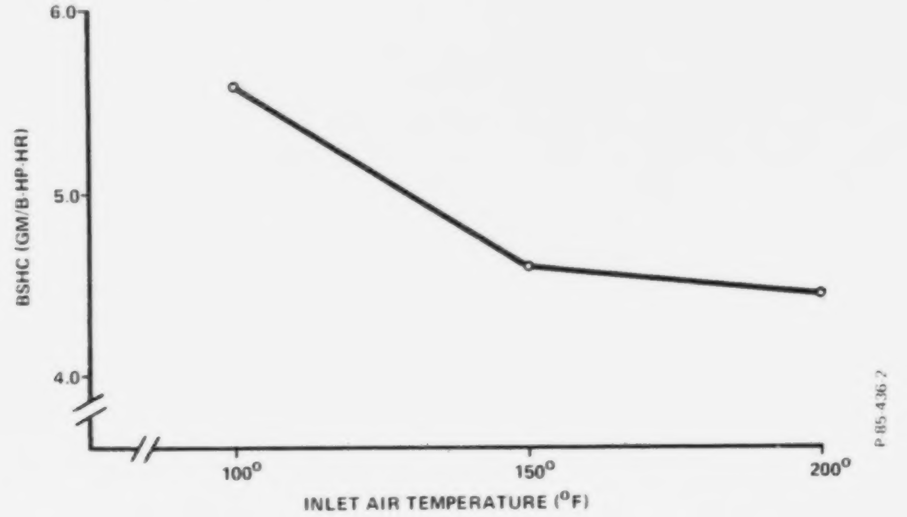

Figure 3-34 - Effect of Inlet Air Temperature on BSHC, 640 rpm, 35 b-ft-lbs (Idle), A/F = 13.9:1, Ignition Timing - 10° BTDC

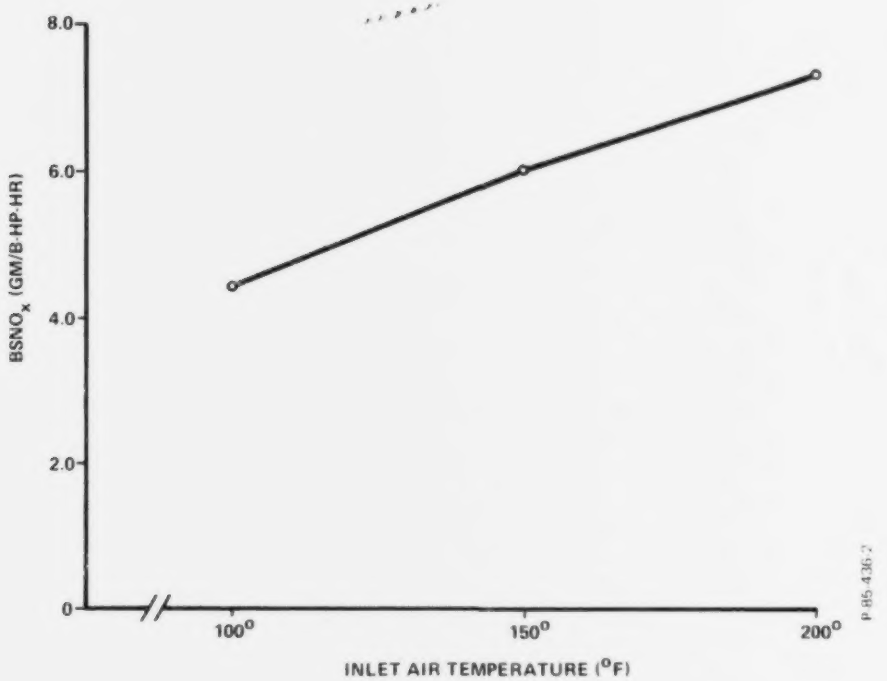

Figure 3-35 - Effect of Inlet Air Temperature on BSNO$_x$, 1200 rpm, 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

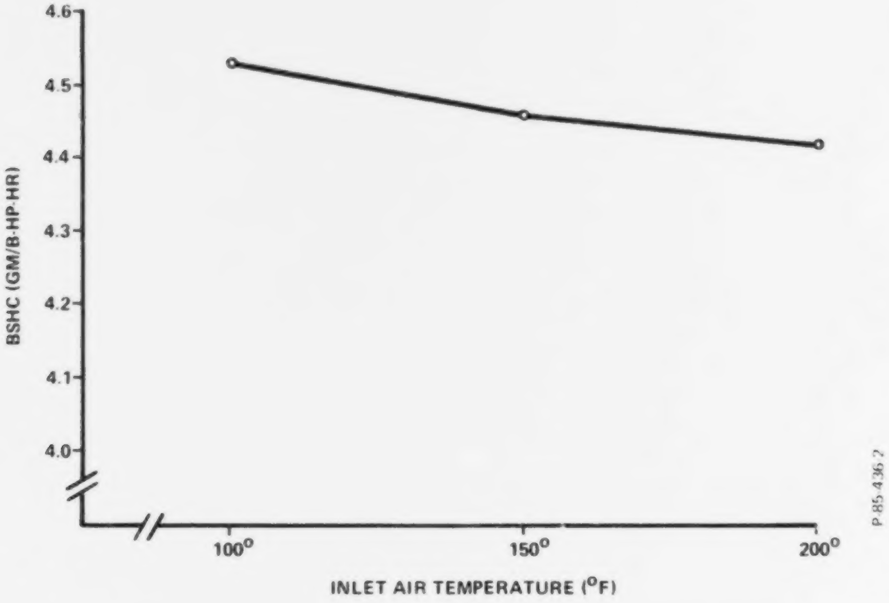

Figure 3-36 - Effect of Inlet Air Temperature on BSHC, 1200 rpm, 100 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

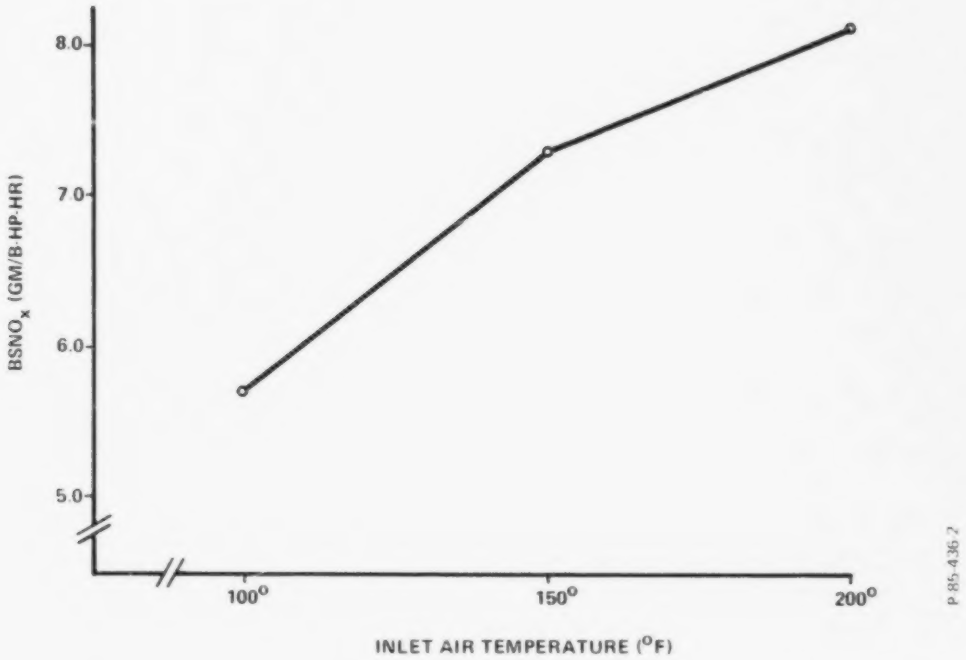

Figure 3-37 - Effect of Inlet Air Temperature on BSNO$_x$, 2000 rpm, 180 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

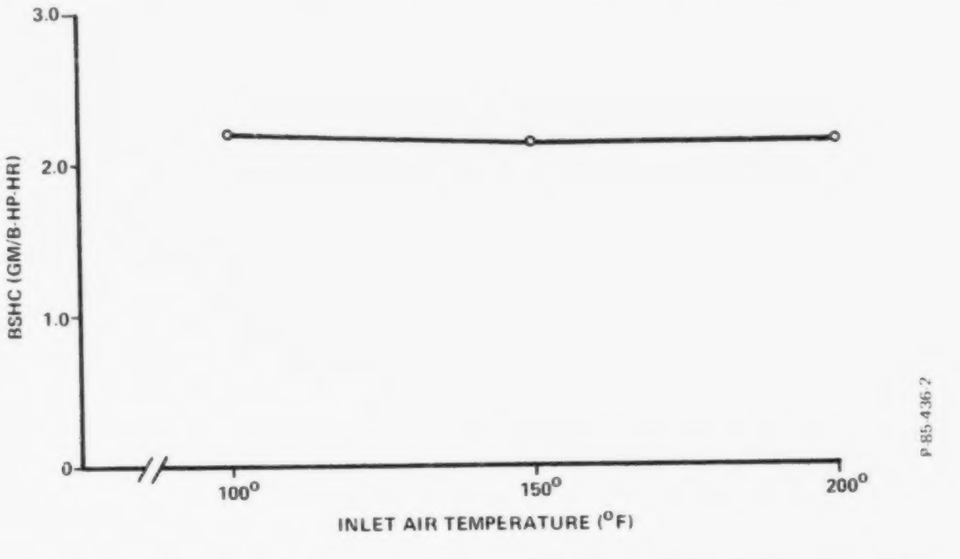

Figure 3-38 - Effect of Inlet Air Temperature on BSHC, 2000 rpm, 180 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

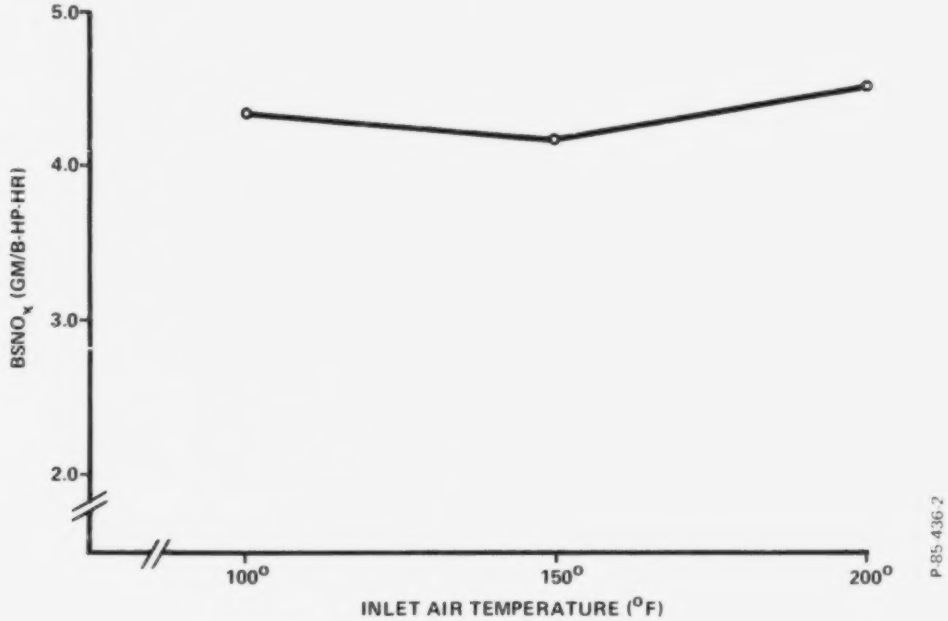

Figure 3-39 - Effect of Inlet Air Temperature on $BSNO_x$, 2000 rpm, 70 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

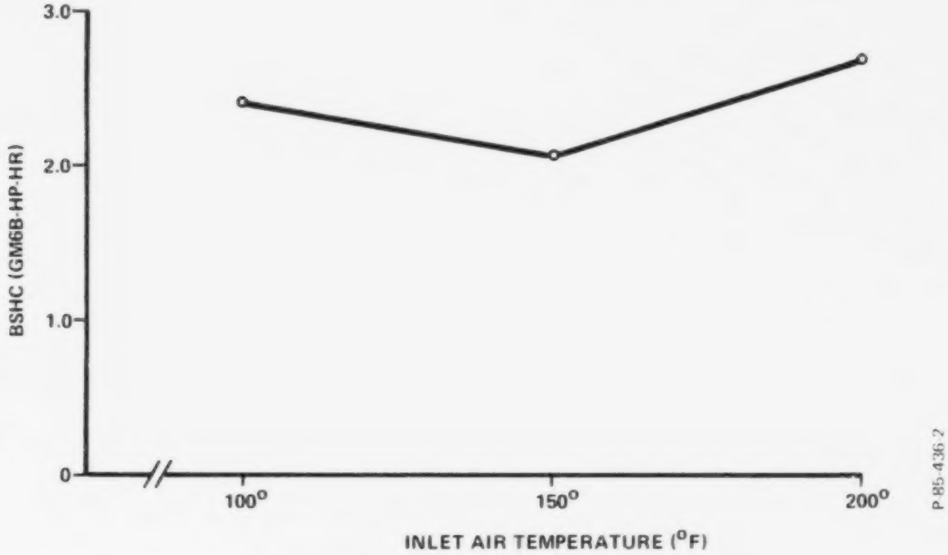

Figure 3-40 - Effect of Inlet Air Temperature on BSHC, 2000 rpm, 70 b-ft-lbs, A/F = 20:1, Ignition Timing - 40° BTDC

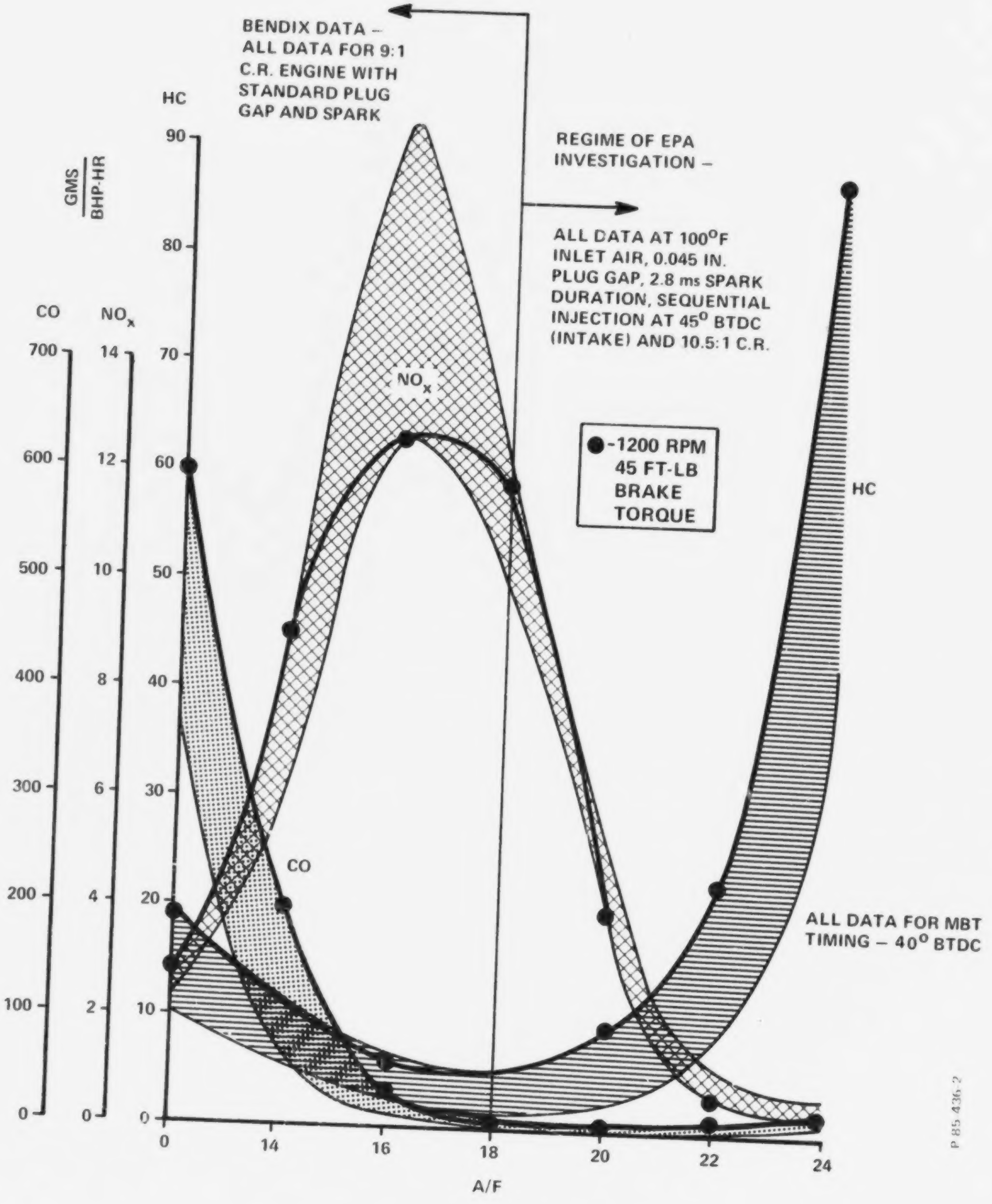

Figure 3-41 - Test Results Correlation

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

It is very difficult to judge from the steady-state results what kind of emissions results could be obtained if the vehicle was driven over an 1970 FTP or 1972 FTP (CVS) driving cycle. However, some judgement can be made by comparing the baseline carburetor, baseline EFI and "best" parameter results. As discussed earlier, the "best" parameter combination with heated air could reduce $BSNO_x$ anywhere from 59 percent to 84 percent of the EFI baseline values.

An average of about 1.4 gm/mile of NO_x was obtained from the four EFI baseline 1970 FTP tests performed at Bendix and EPA. It can be seen that the original goal of this project, which was to lower NO_x emissions to a level of 1.3 gm/mile when a 4000-pound GVW vehicle is operated according to 1970 FTP, can be achieved very easily with the "best" parameter combination. The 1970 FTP tests are, generally, known to produce smaller emissions values compared to the 1972 FTP tests. Considering all these factors, it seems very unlikely that the best parameter combination could meet EPA standards on NO_x emissions for 1976. However, the best parametric combination did, in general, reduce CO mass emissions to an average of 25 percent of the baseline values while HC mass emissions increased over the baseline values by a factor of 1.2 to more than 10.

Inherent presence of O_2 in the exhaust makes the use of catalytic and thermal reactors attractive to oxidize CO and HC.

The exhaust temperatures for the best parameter combination are somewhat lower than the EFI baseline exhaust temperatures; however, they are higher when compared with the carburetor baseline temperatures. About 5 to 10 percent of oxygen is present in the exhaust. With a proper thermal reactor, CO and HC emissions can be reduced considerably. Similarly, a catalytic converter also can be used.

The following conclusions can be made from the parametric tests performed:

(1) With lean-calibrated EFI, compared with a standard carbureted vehicle, NO_x emissions were reduced significantly with little or no changes in HC and CO emissions.

(2) Standard intake and exhaust manifolds on the Ford 429 CID engine did not adversely affect the mass air flow distribution to individual cylinders in the range of engine operation considered for this project.

(3) At steady-state conditions, timed sequential injection did not offer much advantage over the standard group injection.

(4) Increasing the spark plug gap and spark duration/energy from the standard values first decreased NO_x emissions and then, if further increased, increased NO_x emissions. For example, at 1200 rpm and 45 ft-lbs brake torque, the $BSNO_x$ decreased from about 2 gms/b-hp-hr to 1.25 and then increased to 3 for the same set point, the BSHC decreased linearly from 17 to 8 gpm/b-hp-hr.

(5) Heating the inlet air extended the lean-limit operation. NO_x emissions increased and HC emissions decreased. Tendency of detonation increased with heated air.

(6) IVT increased NO_x emissions, MBT spark timing occurred closer to TDC than normal occurrence. IVT increased tendency of the engine to detonate.

4.2 RECOMMENDATIONS

(1) Although intake and exhaust manifolds for the 429 CID engine with EFI were considered satisfactory for this project, in some instances cylinder-to-cylinder A/F variation was more than 1.0. With manifold injection, the design of the intake manifold could be simplified and, perhaps, more uniform distribution of the mass air flow among the cylinders could be obtained. It is recommended that this area be investigated further.

(2) Effect of all or some of the parameters considered should be measured during transient engine operating conditions such as cold start, acceleration, etc.

(3) With the "best" parameters selected actual vehicle tests should be run using injection and ignition control units that would function in transient operating modes.

(4) Investigations should be made to determine optimum combinations of exhaust gas recirculation and air/fuel in the lean operating region to determine if further NO_x control can be achieved.

REFERENCES

1. "Measuring the Effect of Spark Plug and Ignition System Design on Engine Performance," R. R. Burgett, J. M. Leptich, and K. V. S. Sangwan, SAE Paper No. 720007.

2. "Ignition Combustion and Exhaust Emissions of Lean Mixtures in Automotive Spark Ignition Engines," T. Tanuma, K. Sasaki, T. Kaneko, and H. Kawasaki, SAE Paper No. 710159.

3. "Intake Valve Throttling (IVT) - A Sonic Throttling Intake Valve Engine," D. L. Stivender, SAE Paper No. 680399.

4. "The Effect of Mixture Motion upon the Lean Limit and Combustion of Spark Ignited Mixtures," J. A. Bolt, D. L. Harrington, SAE Paper No. 670467.

5. "Exhaust Emissions from a Passenger Automobile Equipped with Electronic Fuel Injection," J. C. Thompson, EPA Report No. 71-12, Division of Motor Vehicle Research and Development, NAPCA, Environmental Protection Agency.

NOMENCLATURE

A/F = air/fuel ratio

ATDC = after top dead center, degrees crankshaft

BSCO = brake specific carbon monoxide, gm/b-hp-hr

BSFC = brake specific fuel consumption, lb/b-hp-hr

BSHC = brake specific total hydrocarbons, gm/b-hp-hr

$BSNO_x$ = brake specific oxides of nitrogen, gm/b-hp-hr

BTDC = before top dead center, degrees crankshaft

CD = capacitive discharge

CO = carbon monoxide

CID = cubic-inch displacement, in^3

CVS = constant volume sampling

ECU = electronic control unit

EFI = electronic fuel injection

FTP = federal test procedure

HC = hydrocarbons

IVT = intake valve throttling

MBT = minimum advance for best torque, degrees crankshaft

NO_x = oxides of nitrogen

APPENDIX A

TEST DESCRIPTION

A.1 TEST SET-UP

A schematic of the test set-up used for the program is shown in Figure A-1. The electric heater was added to the test set-up when intake air heating tests were performed. The heater was installed between the laminar air flow meter and the engine intake manifold.

The test set-up used a magnetic pickup and four steel slugs mounted on the crankshaft damper as a pulse counter for monitoring engine speed. The signal also referenced the crankshaft position of 0 degree BTDC for number one cylinder and when used in conjunction with the spark pulse for number one cylinder, provided the information for monitoring ignition timing. The pulse was also used in conjunction with the fuel injection pulse to monitor the injection timing.

A list of the parameters measured during the testing, the parameter units and the instrumentation used to monitor the parameters is given below:

(1) Air Flow - lb/hr:	
Flow Meter	Meriam laminar flow meter Model 5MC2-4S range of 0 to 400 cfm at 8 inches of H_2O ΔP.
Pressure Transducer	Foxboro Model 613DL 0 to 25 inch H_2O differential
(2) Fuel Flow - lb/hr:	
Flow Meter	FloTron LMF meter Model 10,000 Type II range of 0 to 225 lb/hr at 15 to 20 psig supply
Pressure Transducer	Foxboro Model 61306, 0 to 25-inch H_2O differential
(3) Barometric Pressure - psia	
Pressure Transducer	Taber Model 254, 0 to 25 psia
(4) Torque ft-lb	Pressure Transducer
(5) Flywheel Pulse - pulses/sec	Direct recorded
(6) Spark Pulse	Direct recorded

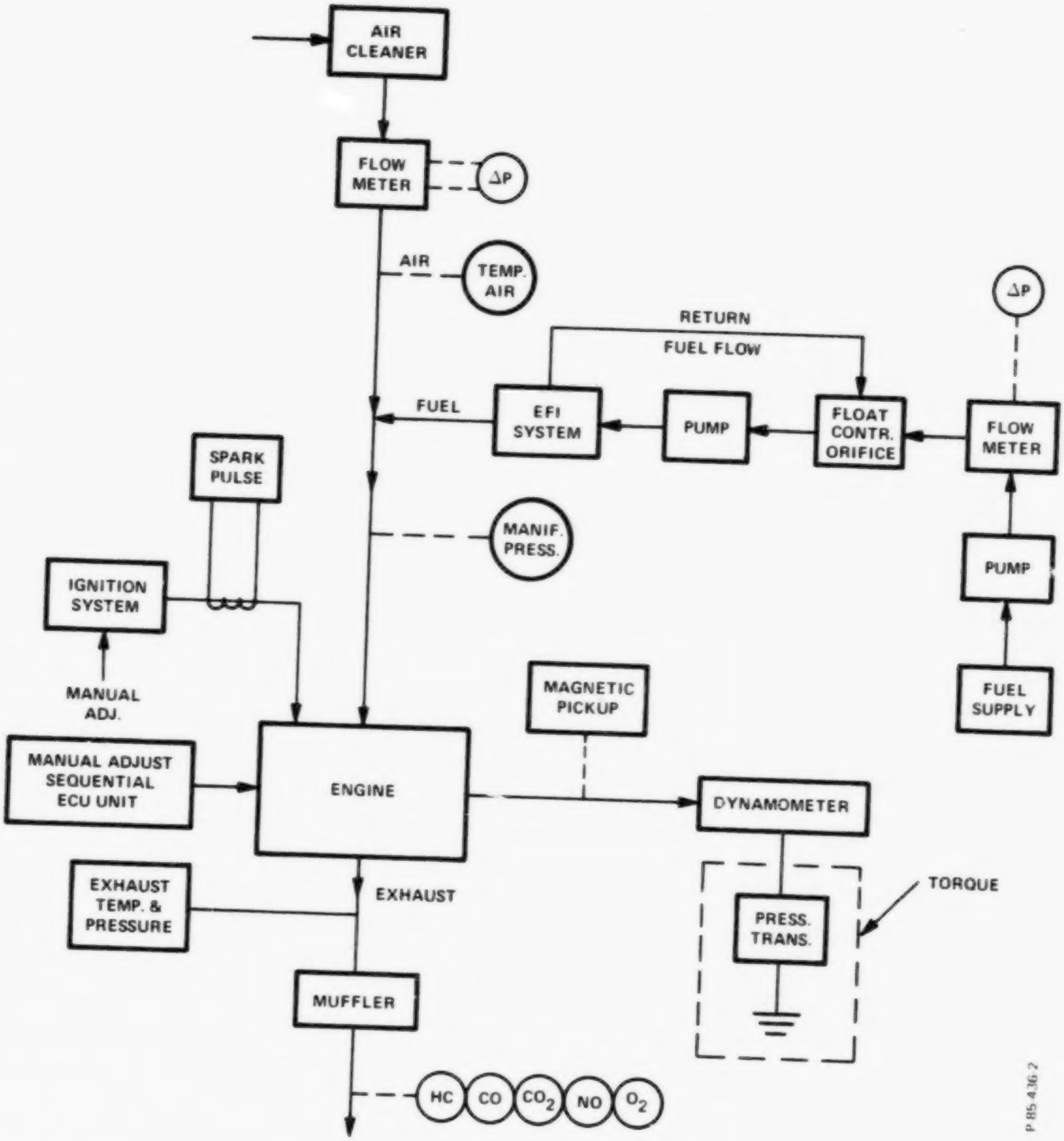
AIR CLEANER
FLOW METER
ΔP
AIR
TEMP. AIR
RETURN
FUEL FLOW
ΔP
FUEL
EFI SYSTEM
PUMP
FLOAT CONTR. ORIFICE
FLOW METER
SPARK PULSE
MANIF. PRESS.
IGNITION SYSTEM
PUMP
MANUAL ADJ.
MAGNETIC PICKUP
FUEL SUPPLY
MANUAL ADJUST SEQUENTIAL ECU UNIT
ENGINE
DYNAMOMETER
EXHAUST TEMP. & PRESSURE
EXHAUST
TORQUE
PRESS. TRANS.
MUFFLER
HC
CO
CO2
NO
O2
P 85 436 2

Figure A-1 - Gas Analyzers (See Figure A-2)

(7)	Injector Pulse Width - msec	Direct recorded
(8)	Manifold Absolute Pressure (MAP) - psia:	Pressure transducer - Taber Model 254, 0 to 25 psia
(9)	NO = ppm:*	Beckman Model 315A NDIR ranges of 0 to 1000, 4000 ppm
(10)	CO - %:*	Beckman Model 315A NDIR ranges 0 to 0.3, 1.2, 3, 12%
(11)	CO_2 - %:*	Beckman Model 315A NDIR ranges of 0 to 3, 16%
(12)	HC - PPMC*	Beckman Model 400 FID ranges 0 to 5, 50, 500 and 5000 ppmC
(13)	O_2 - %:*	Beckman Model 715 ranges 0 to 5 to 25 percent
(14)	Inlet Air Temperature - °F	Thermocouple Chromel Alumel, 0.57 mv at 100°F

All of the above fourteen items were recorded on a CEC Model VRM-3300 14-channel magnetic FM tape recorder. In addition to the above parameters, the engine oil temperature, water outlet temperature, exhaust gas temperature, exhaust back pressure, and dry and wet bulb temperatures were recorded by hand. The schematic of the Scott Emission Analyzer Console and test setup is shown in Figure A-2.

A.2 DATA REDUCTION

The recorded data on the magnetic tape, along with the hand recorded data, were reduced using the BRL hybrid computer. The tape recorded data was read directly into the computer and the manually recorded data was introduced into the data reduction program on key punched cards.

The output from this data reduction was a digital print-out of all the pertinent parameters as shown in Figure A-2. The data was also contained in key punch cards for permanent storage and further data reduction. The key punch cards later were used for computer data plots. Figure A-3 shows one such plot.

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[*] Exhaust analyzers mounted in Scott integrated exhaust analyzer system Model 108-X.

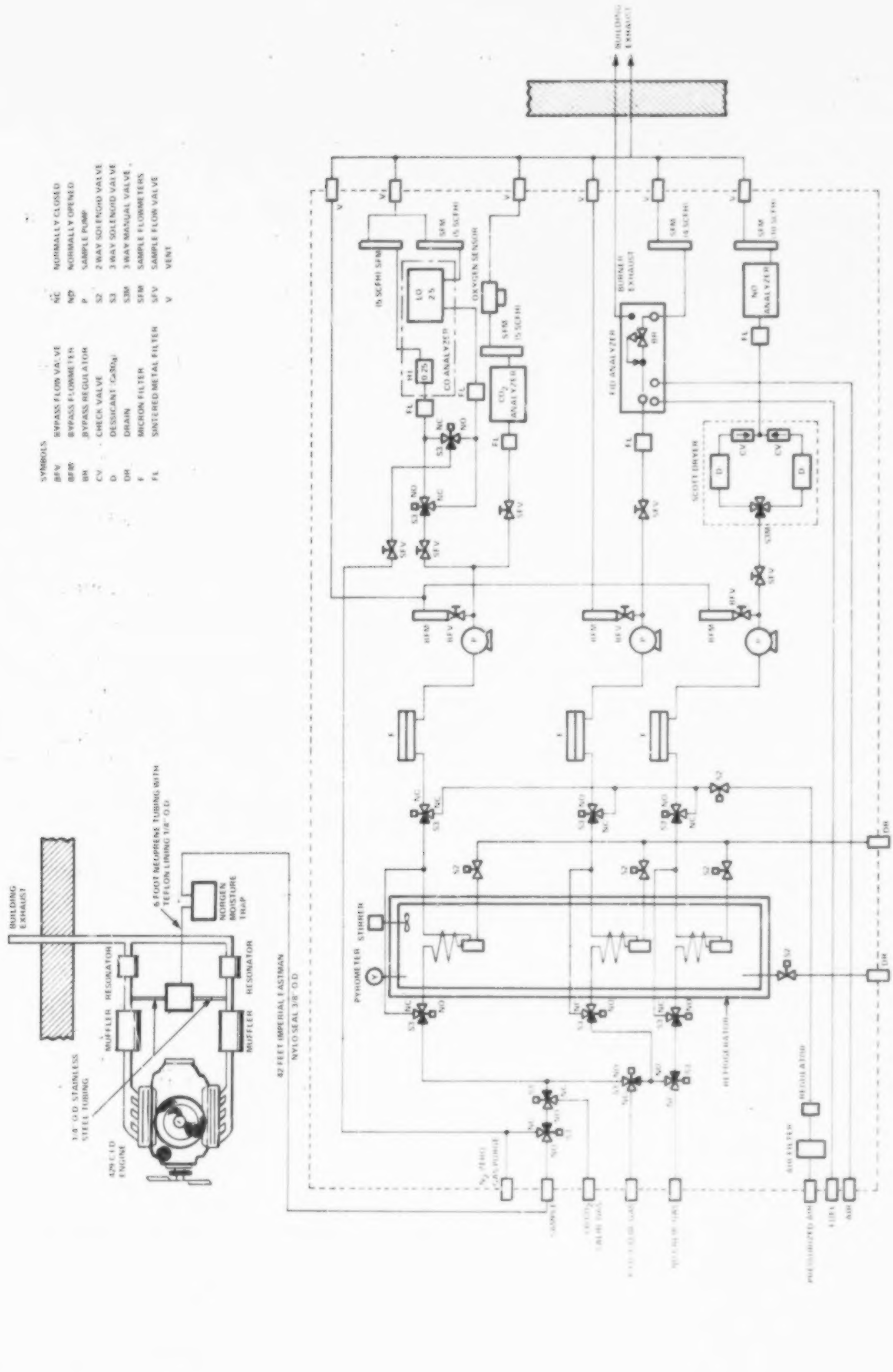

SYMBOLS
BFV BYPASS FLOW VALVE
BFM BYPASS FLOWMETER
BR BYPASS REGULATOR
CV CHECK VALVE
D DESSICANT (CaSO$_4$)
DR DRAIN
F MICRON FILTER
FL SINTERED METAL FILTER
NC NORMALLY CLOSED
NO NORMALLY OPENED
P SAMPLE PUMP
S2 2 WAY SOLENOID VALVE
S3 3 WAY SOLENOID VALVE
S3M 3 WAY MANUAL VALVE
SFM SAMPLE FLOWMETERS
SFV SAMPLE FLOW VALVE
V VENT
BUILDING EXHAUST
6 FOOT NEOPRENE TUBING WITH TEFLON LINING 1/4" O.D.
NORGEN MOISTURE TRAP
RESONATOR
MUFFLER
1/4" O.D. STAINLESS STEEL TUBING
429 C.I.D. ENGINE
42 FEET IMPERIAL EASTMAN NYLOSEAL 3/8" O.D.
PYROMETER
STIRRER
REFRIGERATOR
N_2 ZERO GAS PURGE
SAMPLE
AIR FILTER
REGULATOR
PRESSURIZED AIR
FUEL
AIR
CO ANALYZER
HI 0.25
LO 25
OXYGEN SENSOR
CO_2 ANALYZER
FID ANALYZER
BURNER EXHAUST
NO ANALYZER
SCOTT DRYER
BUILDING EXHAUST

Figure A-2 - Scott Research Laboratories Model 108-X Emissions Analyzer

```
                              ***** EPA PARAMETRIC TEST *****

                        DATE  3/4/72                                    TEST   1

SPEED (RPM) =  640.0                                      BRAKE TORQUE (FT-LB) =      35.000

IGNITION TIMING (DEGREES BTDC) =     0.0                  INJECTOR TIMING (DEGREES BTDC) =   45.0

AIR FLOW (LB/HR) =      62.395                            FUEL FLOW (LB/HR) =       5.090

POWER (BRAKE HP) =       4.265                            INJECTOR PULSE WIDTH (M-SEC) =       2.870

MEASURED AIR/FUEL RATIO =      12.258                     BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =       1.193

INLET AIR TEMPERATURE (DEGREES-F) =   75.0                EXHAUST GAS TEMPERATURE (DEGREES-F) =    687.000

OIL TEMPERATURE (DEGREES-F) =    190.000                  WATER-OUT TEMPATURE (DEGREES-F) =    190.000

MANIFOLD ABSOLUTE PRESSURE (PSIA) =      13.800           BAROMETRIC PRESSURE (PSIA) =     14.200

EXHAUST BACK PRESSURE (IN-WATER) =      1.500             RELATIVE HUMIDITY (GRAINS) =     37.000

                              EMISSION DILUTION FACTOR =      0.949


                                      EMISSION ANALYSIS

NO (PPM) =    270.0000                 NO (GM/HR) =  0.10017E 02             NO (GM/BHP-HR) =  0.23487E 01
NO CORRECTED (PPM) =   217.3344

CO (%) =      5.2179                   CO (GM/HR) =  0.14758E 04             CO (GM/BHP-HR) =  0.34603E 03

CO2 (%) =     11.3845

HC (PPM C) =  5066.0781                HC (GM/HR) =  0.70971E 02             HC (GM/BHP-HR) =  0.16640E 02

O2 (%) =      1.1000

                           CALCULATED AIR/FUEL RATIO =     12.670
```

Figure A-3 - Computer Printout of the Test Results

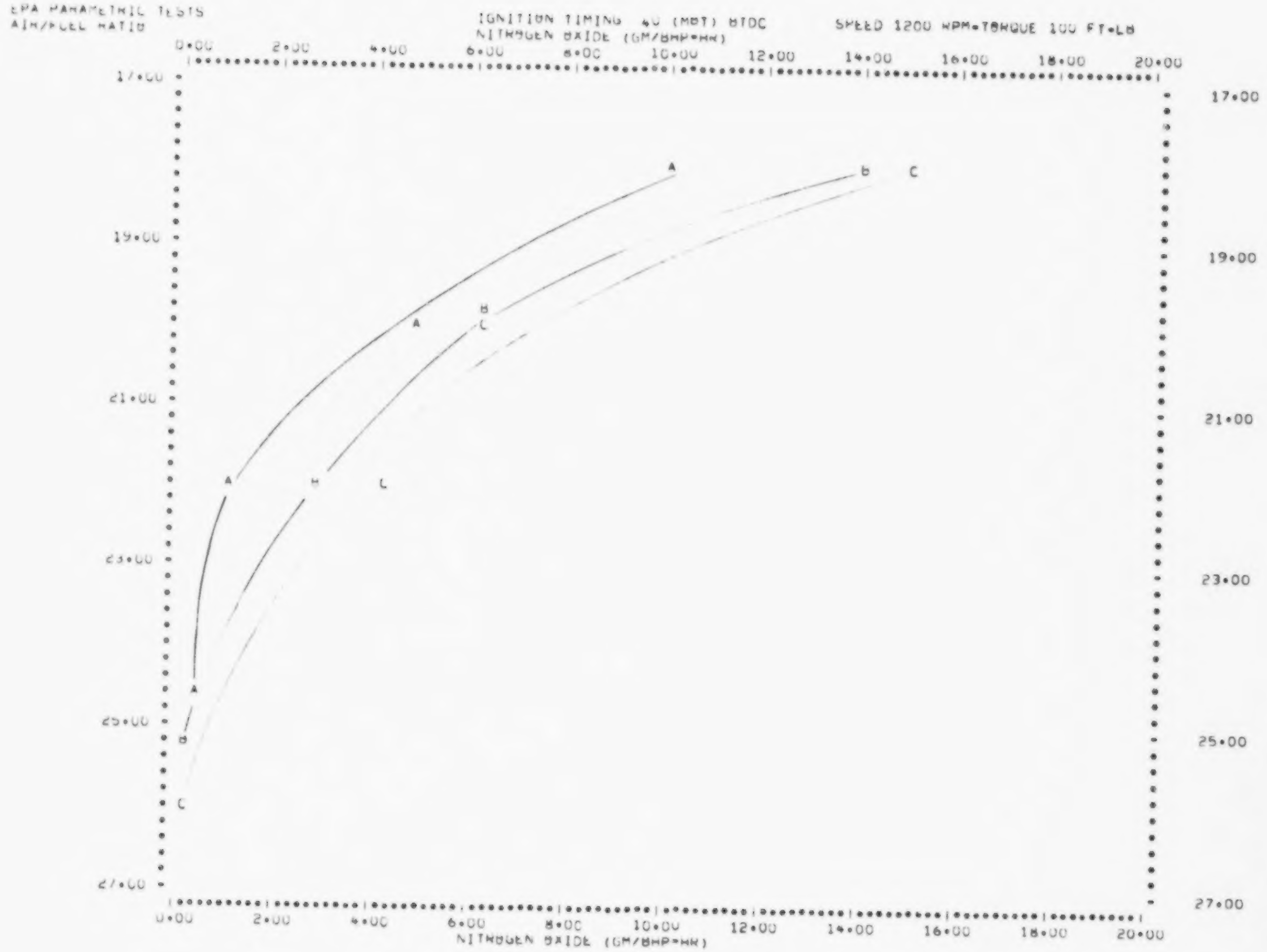


Figure A-4 - Computer Printout of A/F Versus $BSNO_x$ for Various Inlet Air Temperatures

The equations used to program the hybrid computer for data reduction are given below:

(1) Air Flow

$$W_a = \left(\frac{V_1 - V_{01}}{V_{F1} - V_{01}}\right)\left(\frac{P_1}{14.7}\right)\{1 + 0.0033\ (70 - T_f)\}\ SF_1$$

where

W_a = air flow (lb/hr)

V_1 = channel 1 output (V)

V_{01} = zero scale calibration (V)

V_{F1} = full scale calibration (V)

P_1 = barometric pressure (psia)

T_f = inlet air temperature (°F)

SF_1 = scale factor No. 1 (lb/hr)

The factor $\{1 + 0.0033\ (70 - T_f)\}$ is the temperature correction factor in the above expression and is obtained from the temperature correction table supplied with Meriam laminar flow meter. The correction corrects the air flow reading not only for density change but also corrects for viscosity change due to change in temperature.

(2) Fuel Flow

$$W_f = \left(\frac{V_2 - V_{02}}{V_{F2} - V_{02}}\right) SF_2$$

where

W_f = fuel flow (lb/hr)

V_2 = channel 2 output (V)

V_{02} = zero scale calibration (V)

V_{F2} = full scale calibration (V)

S_{F2} = scale factor No. 2 (lb/hr)

(3) Barometric Pressure

$$P_1 = \left(\frac{V_3 - V_{03}}{V_{F3} - V_{03}}\right)(P_{F3} - P_{03}) + P_{03}$$

where

P_1 = barometric pressure (psia)

V_3 = channel 3 output (V)

V_{03} = minimum scale calibration (V)

V_{F3} = maximum scale calibration (V)

P_{03} = minimum calibration pressure (psia)

P_{F3} = maximum calibration pressure (psia)

(4) Brake Torque

$$Q = \left(\frac{V_4 - V_{04}}{V_{F4} - V_{04}}\right) SF_4$$

where

Q = brake torque (ft-lb)

V_4 = channel 4 output (V)

V_{04} = zero scale calibration (V)

V_{F4} = full scale calibration (V)

SF_4 = scale factor No. 4 (ft-lb)

(5) Engine Speed

$$N = \left(\frac{f}{n}\right) 60$$

where

N = engine speed (rpm)

f = pulse frequency of flywheel teeth (cps)

n = number of teeth on flywheel = 4

(6) Ignition Timing

$$\alpha = 90 \frac{b}{a} - \alpha_o$$

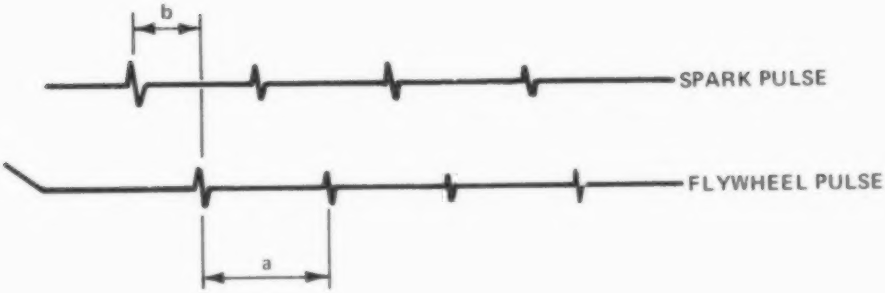
where

α = ignition timing (°btdc)

b = period b (msec)

a = period a (msec)

α_o = initial offset constant (°)


b
SPARK PULSE
FLYWHEEL PULSE
a

(7) Injector Pulse Width and Injection Timing

$$J = \text{pulse width (msec)}$$

$$\beta = 90 \frac{c}{a} - \beta_o$$

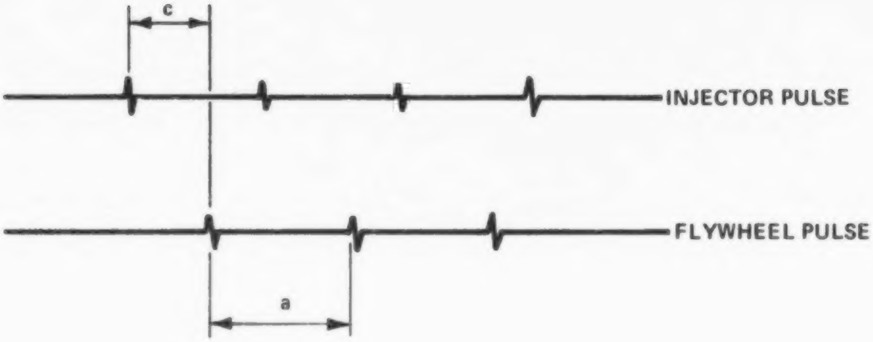
where

β = injection timing (°btdc)

c = period c (msec)

a = period a (msec)

β_o = initial offset constant (°)



(8) Manifold Absolute Pressure (M.A.P.)

$$P_m = \left(\frac{V_a - V_{08}}{V_{F8} - V_{08}} \right) (P_{F8} - P_{08}) + P_{08}$$

where

P_m = manifold absolute pressure (psia)

P_{08} = minimum calibration pressure (psia)

P_{F8} = maximum calibration pressure (psia)

V_8 = channel 8 output (V)

V_{08} = minimum scale calibration (V)

V_{F8} = maximum scale calibration (V)

(9) $\underline{NO_x}$

$$NO = V_9 \times SF_9$$

where

NO = nitric oxide by volume (ppm)

V_9 = channel 9 output (V)

SF_9 = Scale factor No. 9 corresponding to voltage V_9 from NO analyzer calibration tables $\frac{ppm}{V}$

$$NO_c = NO \times K_H \times D.F.$$

where

NO_c = nitric oxide by volume with humidity and dilution correction factors

K_H = humidity correction factor = $\frac{1}{1 - 0.0047\ (H-75)}$, H being grains of moisture per pound of dry air

$$D.F.^* = \text{dilution factor} = \frac{14.5}{\%\ CO_2 + (0.5)\ \%\ CO + \frac{HC(ppm\ C)}{10{,}000}}$$

---

*Dilution factor is used to correct concentration emissions data to a stoichiometric mixture, so that a fair comparison of concentration data can be made at different A/F.

$$NOX_m = \frac{NO}{10^6} \times V_E \times M_{NO_2} \times CF'_\omega \times K_H$$

where

NOX_m = oxides of nitrogen in gm/hr

CF'_ω * = water correction factor selected from Table A-1.

V_E = exhaust flow (ft^3/hr) = $\frac{W_a + W_f}{0.075**}$

M_{NO_2} = density of NO_2 (gm/ft^3) = 54.16

Table A-1 - Values of CF'_ω and CF_ω for Different A/F

A/F	18:1	19:1	20:1	21:1	22:1	23:1
CF'_ω	0.897	0.902	0.907	0.913	0.919	0.923
CF_ω	0.904	0.910	0.914	0.920	0.926	0.931

---

*The water correction factors are applied to mass emissions because when measuring concentrations, water is removed from the exhaust sample. In case of CO, CO_2 and HC, water is removed by cooling exhaust to 32°F which does not remove all the water. In the case of NO, the sample is further passed through "dri-rite" which removes all the water. The values of CF'_ω and CF_ω were calculated by knowing water content from chemical reactions taking place at various A/F.

**The density of exhaust was found to be 0.075 ft^3/hr at stoichiometric A/F. For mixtures leaner than stoichiometric, negligible change in the density of exhaust was found. Therefore, 0.075 ft^3/hr was used as density of exhaust for all A/F considered in this project.

(10) CO

$$CO = V_{10} \times SF_{10}$$

where

CO = carbon monoxide by volume (%)

V_{10} = channel 10 output (V)

SF_{10} = scale factor NO. 10 corresponding to voltage V_{10} from CO analyzers calibration Tables (%/V)

$CO_c = CO \times D.F.$

where

CO_c = carbon monoxide concentration by volume (%)

$$CO_m = \frac{CO}{100} \times V_E \times M_{CO} \times CF_\omega$$

where

CO_m = carbon monoxide in gm/hr

V_E = exhaust flow (ft^3/hr)

M_{CO} = density of CO = $32.97 \frac{gm}{ft^3}$

CF_ω = water correction factor = 0.884

(11) $\underline{CO_2}$

$$CO_2 = V_{11} \times SF_{11}$$

where

CO_2 = carbon dioxide by volume (%)

V_{11} = channel 11 output (V)

SF_{11} = scale factor No. 11 corresponding to voltage V_{11} from CO_2 analyzer calibration tables (%/V)

$$(CO_2)_c = CO_2 \times D.F.$$

where

$(CO_2)_c$ = carbon dioxide concentration by Volume (%)

(12) HC

$$HC_c = \left(\frac{V_{12} - V_{012}}{V_{F12} - V_{012}}\right) SF_{12} \times D.\ F.$$

where

HC_c = total hydrocarbon concentration by volume (ppm C)

SF_{12} = Scale factor No. 12 (ppm C)

V_{12} = channel 12 output (V)

V_{012} = zero scale calibration (V)

V_{F12} = full scale calibration (V)

$$HC_m = \frac{HC}{10^6} \times V_E \times M_{HC} \times CF_\omega$$

where

HC_m = total hydrocarbon in gm/hr

CF_ω = water correction factor

V_E = exhaust flow (ft^3/hr)

M_{HC} = density of HC = 16.33 $\frac{gm}{ft^3}$ (Indolene)

(13) O_2

$$O_2 = \left(\frac{V_{13} - V_{013}}{V_{F13} - V_{013}}\right) (SF_{13})$$

where

O_2 = oxygen by volume (%)

V_{13} = channel 13 output (V)

V_{013} = zero scale calibration (V)

V_{F13} = full scale calibration (V)

SF_{13} = scale factor No. 13 (%)

(14) Inlet Air Temperature

$$T_F = \left(\frac{V_{14} - V_{014}}{V_{F14} - V_{014}}\right) (T_{F14} - T_{014}) + T_{014}$$

where

T_F = inlet air temperature (°F)

V_{14} = channel 14 output (V)

V_{014} = minimum scale calibration (V)

V_{F14} = maximum scale calibration (V)

T_{014} = minimum calibration temperature (°F)

T_{F14} = maximum calibration temperature (°F)

(15) Additional Calculations

A/F

$$A/F = \frac{W_a}{W_f}$$

where

A/F = air fuel ratio

W_a = air flow (lb/hr)

W_f = fuel flow (lb/hr)

A/F Ratio From Exhaust Analysis

$$(A/F)_e = F_b \left\{ 11.492\, F_c \left(\frac{1 + E/2 + D}{1 + E} \right) + \frac{120\ (1 - F_C)}{3.5 + E} \right\}^*$$

where

$(A/F)_e$ = A/F from exhaust analysis

$$F_b = \frac{\%CO + \%CO_2}{\%CO + \%CO_2 + \frac{HC\,(ppm\ C)}{10{,}000}}$$

F_c = fraction of carbon in fuel = 0.867 (Indolene)

$$E = \frac{\%CO}{\%CO_2}$$

$$D = \frac{\%O_2}{\%CO_2}$$

Brake Horsepower

$$BHP = \frac{QN}{5252}$$

where

BHP = brake horsepower

---

*"Air-Fuel Ratios from Exhaust Gas Analysis," R. S. Spindt, SAE Paper 650507.

Q = brake torque (lb-ft)

N = engine speed (rpm)

Brake Specific Fuel Consumption

$$BSFC = \frac{W_f}{BHP}$$

where

BSFC = brake specific fuel consumption (lb/bhp-hr)

W_f = fuel flow (lb/hr)

BHP = brake horsepower

HC, CO and NO_x Emissions on gm/bhp-hr Basis

$$HC_{mh} = \frac{HC_m}{BHP}$$

$$CO_{mh} = \frac{CO_m}{BHP}$$

$$NOX_{mh} = \frac{NOX_m}{BHP}$$

where

HC_{mh} = HC emissions $\frac{gm}{bhp\text{-}hr}$

HC_m = HC emissions $\frac{gm}{hr}$

CO_{mh} = CO emissions $\frac{gm}{bhp\text{-}hr}$

CO_m = CO emissions $\frac{gm}{hr}$

NOX_{mh} = NO_x emissions $\frac{gm}{bhp\text{-}hr}$

NOX_m = NO_x emissions $\frac{gm}{hr}$

A.3 TEST PROCEDURE

The test procedure varied somewhat for different phases of the program because several different parameters were varied and in some cases it was easier to vary certain parameters first than others. However, generally, the same test procedure as described in Appendix C for the baseline tests was followed.

APPENDIX B

AIR-MANAGEMENT EVALUATION OF A 1970 FORD C.I.D. ENGINE WITH AN EFI INTAKE MANIFOLD AND THROTTLE BODY

B.1 INTRODUCTION

One of the ways to reduce NO_x emissions from a spark-ignition engine is to let it run as lean as possible. To run an engine as lean as possible without a misfire, even distribution of air/fuel ratio among the engine cylinders is of prime importance.

The Bendix EFI (Electronic Fuel Injection) system can be calibrated to give even fuel distribution to the individual cylinders to within one percent of each other. Therefore, it is the air distribution among the cylinders that becomes of significant importance.

The present Ford 429 C.I.D. engine intake manifold is shown schematically in Figure B-1. The firing order is 15426378.

Some effort is made in designing the manifold to keep physical size and shape of each runner and the branches identical. However, when a close look is taken at the firing order, the runners see different dynamic pulsation that probably affect air flow distribution. In the runners a and b, feeding cylinders 1-6 and 4-7, respectively, the period between the pulses is uniform. In runners c and d,

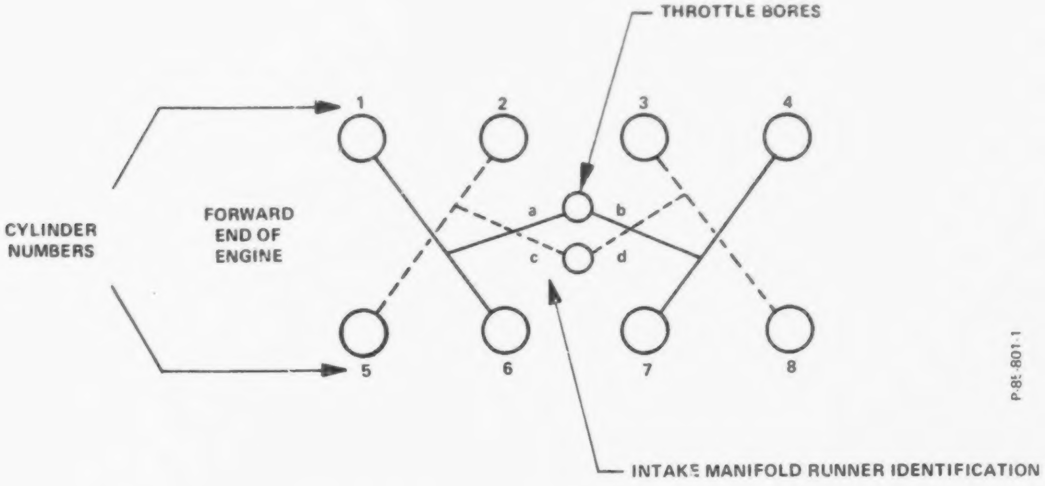


Figure B-1 - Ford 429 C.I.D. Engine Cylinder Identification two pulses occur at one-half the period of runners a and b and then there is a delay equal to 1.5 the period of runners a and b. Of course, the manifold has been designed to distribute a carbureted air/fuel mixture and it is possible that branch and runner passages are sized to correct for air/fuel ratio non-uniformities. These design techniques can affect the mass air flow rates for the special case where no fuel is required to be carried with the air until just before introduction into the cylinder (manifold fuel injection).

Although the manifold is suspected by contributing to most of the air flow non-uniformity, the engine itself cannot be ignored The engine is the air pump and its pumping characteristics can be subject to variations between cylinders related to ring and valve leakages and dimensional variations.

Another phenomenon that may affect the air distribution on an operating engine would be different heat transfer rates to individual intake manifold branches. This might cause the air entering in various cylinders to be of different density. The exhaust manifolds also contribute to the uneven air distribution due to possible uneven back pressure resulting from the dynamic flow conditions that exist in the exhaust manifolds. Before undertaking an investigation into operating improvements related to variations of air/fuel ratio and other parameters to define an extended lean operating regime, this evaluation of air flow uniformity was done to disclose any unusual anomalies that could limit the value of the remainder of the tests.

B.2 SUMMARY

The air management study was undertaken to evaluate the influence of standard intake and the exhaust manifolds on the distribution of mass air flow to individual cylinders for a 1970 Ford 429 C.I.D. engine.

The motored engine tests were conducted at various throttle settings, which simulated the various driving modes to evaluate mass distribution of air to individual cylinders by the intake manifold. Except for the idle condition, the maximum percent variation in mass air flow from cylinder to cylinder due to the intake manifold was found to be about 4 percent. The maximum percent variation at idle was found to be 10.5. It was concluded that the intake manifold was satisfactory for the purpose of this project.

Tests were conducted on the operating engine to evaluate exhaust manifolds using injectors matched to deliver fuel flow within one percent. Individual cylinder-to-cylinder exhaust was sampled to determine individual air/fuel ratio from each cylinder. Tuned exhaust headers were used as a baseline. It was recognized that these manifolds would interfere least with the exhaust flow from each cylinder and would provide the least back pressure variation. Hence, minimum effect on air/fuel ratio distribution will be felt using these headers. Similar air/fuel ratio measurements were made using the standard exhaust manifolds and the exhaust system. It was found, as shown later, that the air/fuel ratio variations were not greatly different than those with the tuned headers. It was concluded, therefore, that the standard exhaust system, under operating conditions, did not affect the air distribution significantly in the engine.

Thus, it was finally concluded that the standard intake and the exhaust manifolds have only a nominal effect on the distribution of mass air flow in the operating range of the tests planned for this project.

B.3 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were made from the results of the investigation:

(1) In the operating range of the parametric testing (600 to 2000 rpm), except for idle, the maximum error due to the intake manifold in air mass distribution to individual cylinders is about 4 percent or ±2 percent from the average. The error is believed to be primarily due to the different dynamic phenomena taking place in different manifold branches. A plenum-type manifold with individual runners for each cylinder branching from the plenum might remove this deficiency. However, to design, fabricate and test such a manifold to reduce a 4 percent variation would be beyond the scope of this project. Therefore, there will be no attempt to alter the intake manifold design.

(2) From the compression tests on the engine, it was concluded that the engine is in sound physical shape.

(3) From the tests run on the two different exhaust manifolds, it can be concluded that an exhaust system with inherent low back pressure and of construction in which the dynamic effects from each cylinder are kept isolated for a longer period of time (tuned header) has no apparent advantage over a standard exhaust system within the engine operating range of this project. It is recommended, therefore, that the standard exhaust system be used for the rest of the parametric tests.

B.4 TEST METHOD AND DATA ANALYSIS

B.4.1 Test Method

To evaluate the existing intake manifold, engine motoring tests were performed. Since Bendix dynamometer facilities were not ready, the Ford engine was coupled to another engine and motored. The test set-up is shown in Figure B-2. Because of the pulsating flow into and out of a cylinder, measurement of actual mass air flow into each cylinder was very difficult to achieve. Instead, a scheme was devised to measure the peak compression pressure.

The Ford engine was instrumented to measure inlet ai. temperature and peak compression pressure. The engine block temperature and the coolant out temperatures were monitored and maintained

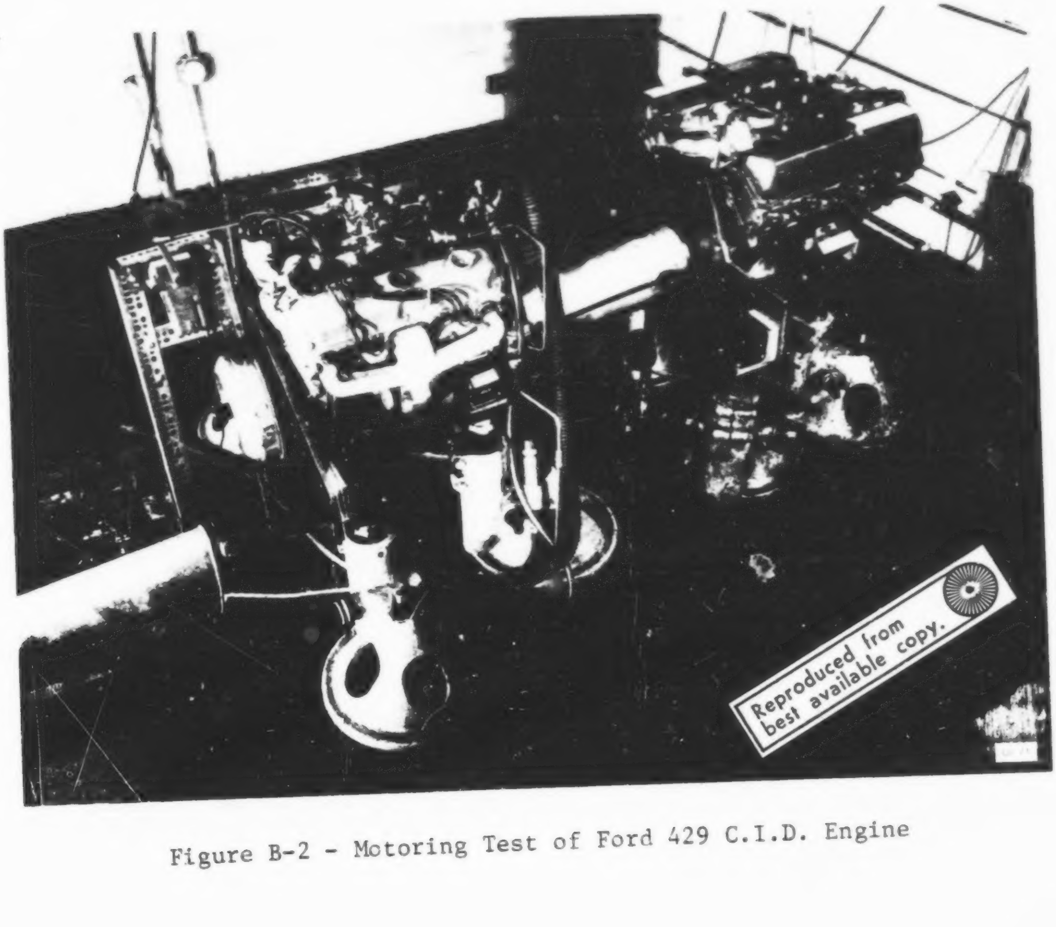


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Figure B-2 - Motoring Test of Ford 429 C.I.D. Engine at simulated operating temperatures. Also, the barometric pressure was recorded. A fast responding strain gage type transducer was used to measure the peak compression pressure. The pressure was recorded on a fast responding light beam type recorder. The inlet air temperature was continuously recorded on a Sanborn recorder. The engine speed was accurately measured with a magnetic pick-up in conjunction with four steel slugs on the crankshaft pulley and an electronic counter.

The tests first were run without the intake or the exhaust manifolds and then with only the intake manifold and the EFI throttle body (no venturis). The tests were run for four different throttle positions. Closed throttle (idle), wide open throttle and two part-throttle positions were chosen. The two part-throttle positions were representative of a smooth acceleration from 30 mph and 50 mph cruise conditions.

To record data, the engine speed was set and the throttle positioned, such as for 50 mph cruise, to give the desired manifold absolute pressure (M.A.P.). Then, with these conditions, steady state data were recorded for stabilized conditions of M.A.P., water coolant outlet temperature and engine speed at speeds of 600, 1000, 1500, 2000, and 3000 rpm. The evaluation of the flow distribution uniformity characteristics of the manifolds is hampered somewhat by the basic pumping variations between cylinders that were observed during the motored-engine tests of the bare engine (no manifolds). Figure B-3 shows the variation in cylinder peak compression pressures observed for the bare engine.

In order to more clearly define the influences of the manifolds and the throttle body, an analytical procedure was devised that normalizes the data to effectively eliminate the bare engine variations. This is discussed below.

B.4.2 Data Evaluation Theory

The analysis that follows was suggested by Dr. Jose Bascunana of EPA to analyze and evaluate the intake manifold for mass air flow distribution from cylinder to cylinder.

For a given cylinder at the start of the compression stroke, from the equation of state for an ideal gas:

$$P_i \; V_i = M \; T_i \; R \qquad (1)$$

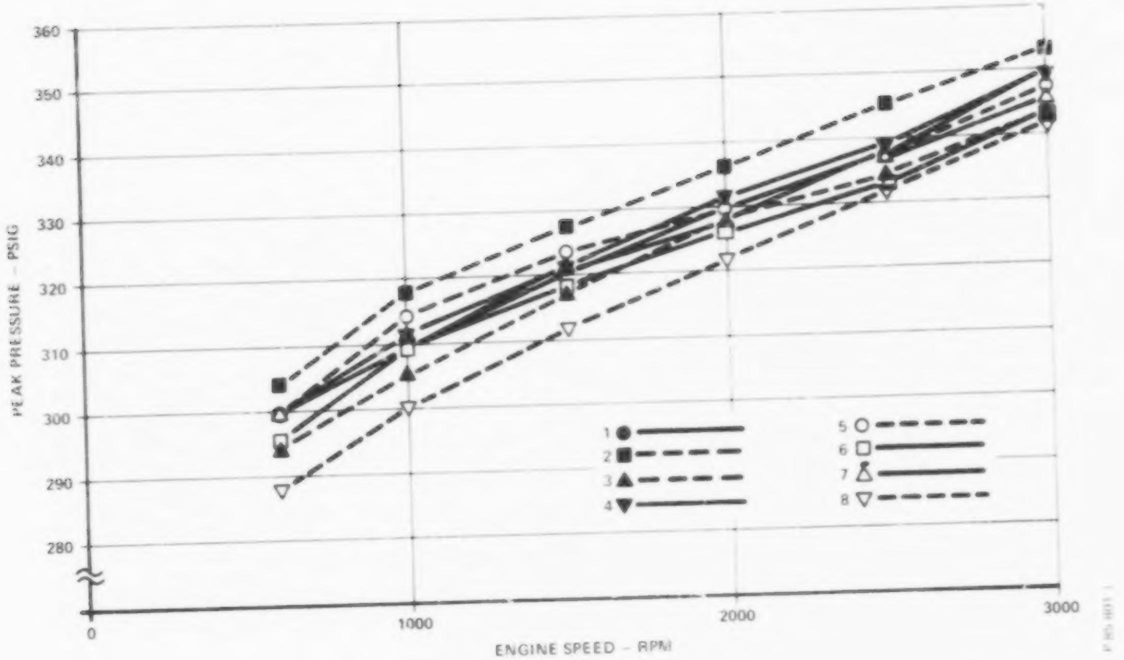

Figure B-3 - Cylinder Peak Pressure 1970 429 C.I.D. Ford Engine - No Manifolds

where P_i is the absolute pressure at the start of the compression, V_i is the volume at the start of the compression, M is the mass of the charge inducted, R is the gas constant, and T_i is the absolute temperature of the air mass at the start of the compression stroke.

Similarly, at the end of the compression stroke, we have:

$$P_c V_c = M T_c R \qquad (2)$$

where subscript c corresponds to the values of absolute pressure, absolute temperature and the volume at the end of the compression stroke.

Assuming that the compression is an isentropic process, we can write,

$$\frac{T_c}{T_i} = \left(\frac{V_i}{V_c}\right)^{k-1} = (r)^{k-1} \tag{3}$$

where k is the polytropic exponent, and r is the compression ratio of that cylinder.

$$T_c = T_i\ (r)^{k-1} \tag{4}$$

Substituting equation (4) into equation (2), we have

$$P_c\ V_c = M\ T_i\ R\ (r)^{k-1} \tag{5}$$

or

$$M = \frac{P_c\ V_c}{T_i\ R}\left(\frac{1}{r}\right)^{k-1} \tag{6}$$

From equation (6) we can write two equations for any given cylinder for two different conditions, subscripts 1 and 2. For example, let subscript 1 refer to the condition where only the intake manifold is installed and subscript 2 the condition where both the intake and the exhaust manifolds are installed.

$$M_1 = \frac{P_{c1}\ V_{c1}}{T_{i1}\ R}\left(\frac{1}{r_1}\right)^{k-1} \tag{7}$$

and

$$M_2 = \frac{P_{c2}\ V_{c2}}{T_{i2}\ R} \ \frac{1}{r_1}^{\ k-1} \tag{8}$$

Of course, since equations (7) and (8) are for the same cylinder, $V_{c1} = V_{c2}$ and $r_1 = r_2$. Simplifying and dividing equation (7) by equation (8), we have

$$\frac{M_1}{M_2} = \frac{P_{c1}}{P_{c2}} \times \frac{T_{i2}}{T_{i1}} \tag{9}$$

Thus, we have a ratio of mass of air inducted under two different external conditions for the same cylinder. In this case, the external condition effectively gives the influence of the intake manifold on the charge inducted into that particular cylinder. M_1/M_2 ratios can be found similarly for all remaining cylinders. The comparison of these ratios from one cylinder to another shows the influence of the intake manifold on the mass air distribution to each cylinder.

The data obtained using the Sanborn recorder and the light beam recorder were reduced by hand. Using this and other hand recorded data, the ratio M_1/M_2 was computed for each cylinder at every engine rpm for a given throttle condition. The time share computer was used to perform the calculations. For every speed at the given throttle condition, maximum percent deviation in M_1/M_2 between the cylinders was computed.

Thus, from the motored engine data and the above method of analysis, the intake manifold was evaluated for its role in distributing the inducted air mass to the individual cylinders at the given operating conditions. Following the test and evaluation of the intake manifold, the influence of the exhaust manifold and other engine parameters, such as individual cylinder compression, were evaluated on the operating engine. For these evaluations a set of fuel injectors (manifold injection), matched to flow within a one percent spread, were installed and, using exhaust gas analysis, air/fuel ratio was determined from each cylinder. Variations in air/fuel ratio more than the estimated combined error due to the intake manifold and the injectors was attributed to additional variations in the air flow from one cylinder to another caused by the exhaust manifolds or variations in the engine geometry, or both.

B.5 ANALYSIS AND DISCUSSION OF THE RESULTS

Figure B-4 shows the plot of maximum percent deviation of M_1/M_2 as a function of engine rpm for all four throttle positions. The percent deviation represents the influence of the intake manifold on the mass air flow to individual cylinders. In the operating range of the parametric tests, except for idle, the M_1/M_2 deviation is about 4 percent. At idle, the deviation is about 10.5 percent and then as the speed increases, for the same throttle position, it levels off to about 7 percent.

To see the effect of engine rpm on the air distribution of the intake manifolds, Figures B-5, B-6, B-7, and B-8 were plotted for: idle; for a throttle position providing 10.5 psia M.A.P., at 1200 rpm (smooth acceleration from 30 mph); for a throttle position providing 9.7 psia M.A.P. at 2000 rpm (50 mph cruise), and for wide open throttle (W.O.T.), respectively. On the Y-axis, a normalized parameter $[(M_1/M_2) \div (\text{Avg. } M_1/M_2)]$ is plotted and on the X-axis the engine rpm is plotted. The variable parameter is the cylinder number. Cylinders 2, 3, 5, and 8 are plotted with broken lines and cylinders 1, 4, 6, and 7 with solid lines. These two sets of cylinders represent runners c-d and a-b, respectively in Figure B-1.

As previously discussed the two sets of runners see different dynamic phenomena. An attempt is made from these plots to recognize any effect of this. Except for the idle and the wide open throttle conditions, a trend is obvious. Figures B-6 and B-7 clearly show, for speeds greater than 2000 rpm, that the intake manifold runners a and b tend to allow relatively more mass air flow into cylinders 2, 3, 5, and 8. For speeds of 2000 rpm and 2500 rpm, the deviation is about +2 percent about the nominal and at 3000 rpm the deviation is about +3 percent. Although these dynamic effects do occur in this manifold, for the purpose of this project the engine will not be operated at speeds greater than 2000 rpm, and the total percent deviation in mass air flow due to the intake manifold would only be about 4 percent at all conditions except at idle. To attempt to refine the intake manifold design to correct this deficiency is believed to be beyond the scope of this project.

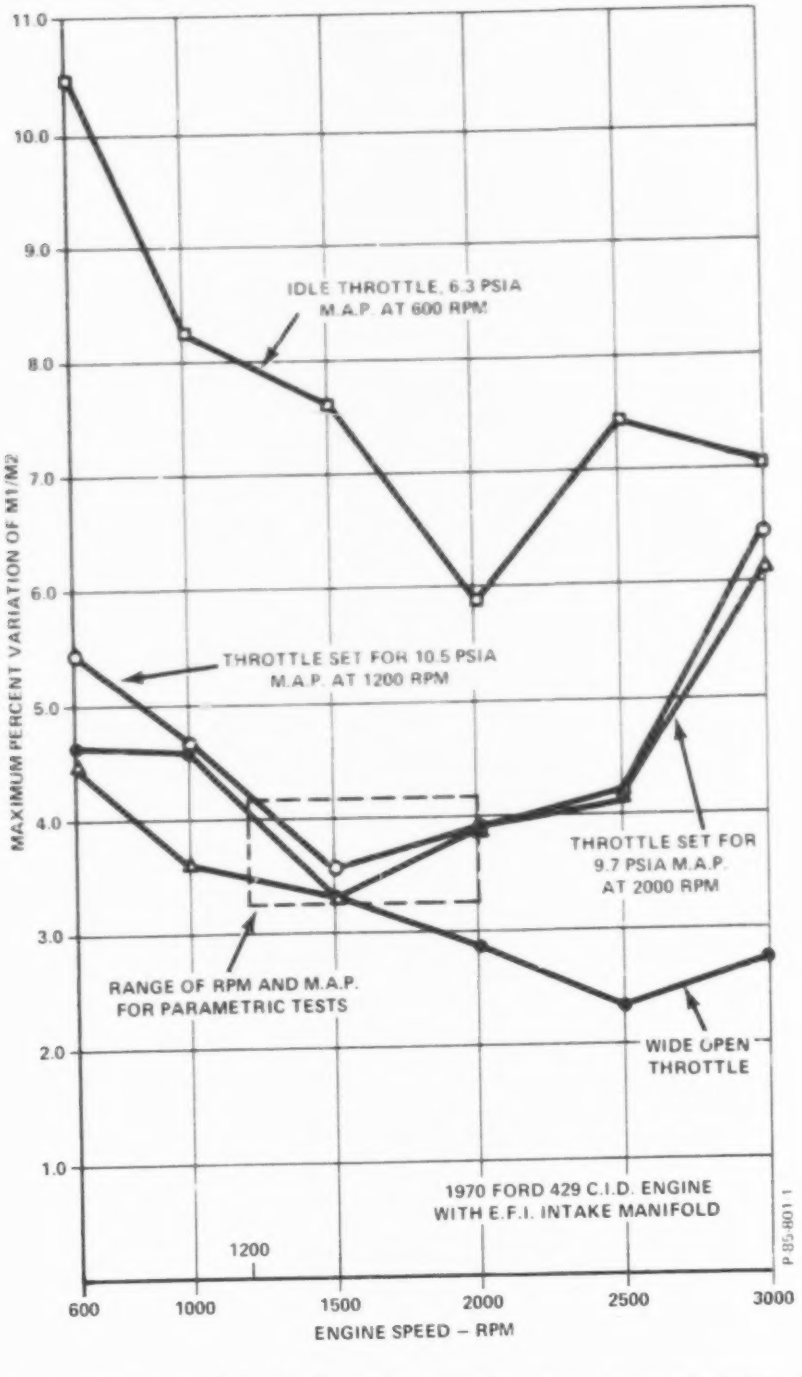

Figure B-4 - Effect of Intake Manifold on Maximum Plus to Minus Variation Between Cylinders for the Ratio M_1/M_2 at Various Operating Conditions

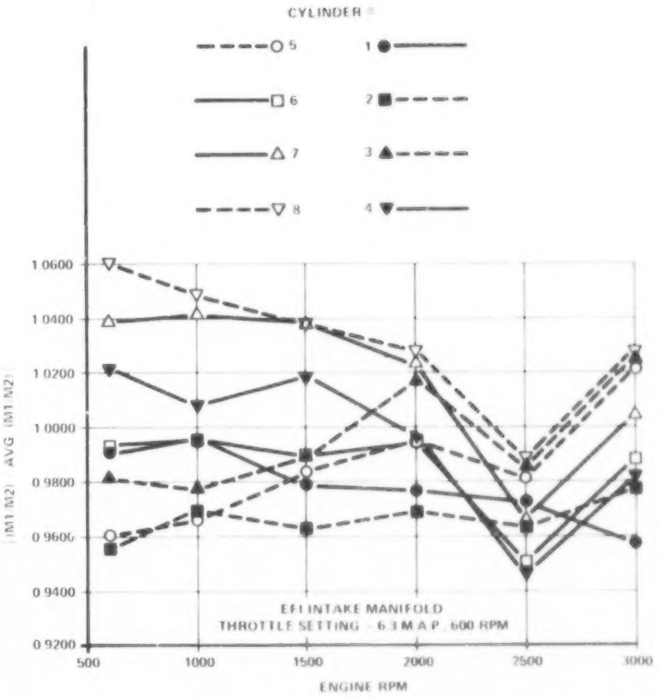

Figure B-5 - Effect of Speed on Cylinder Mass Air Flow
1970 Ford 429 C.I.D. Engine
E.F.I. Intake Manifold

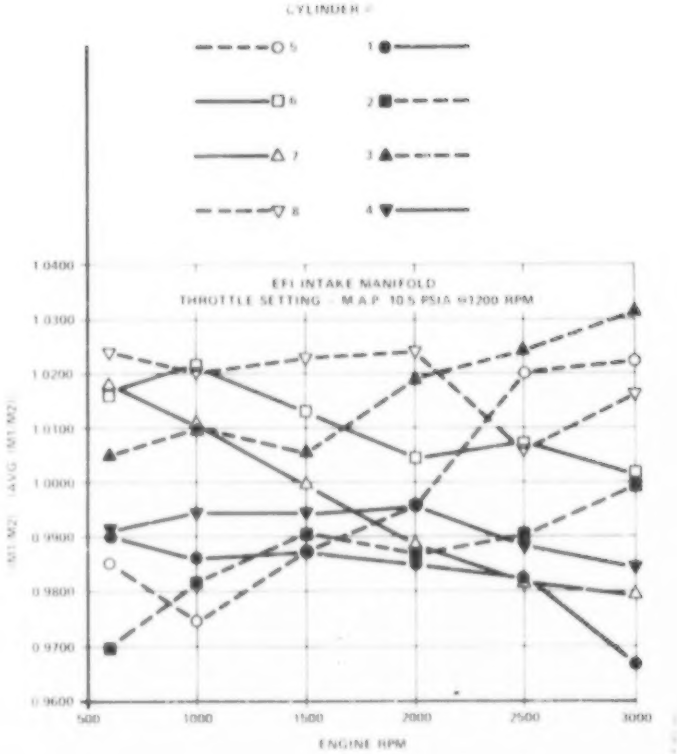

Figure B-6 - Effect of Speed on Cylinder Mass Air Flow
1970 Ford 429 C.I.D. Engine
E.F.I. Intake Manifold

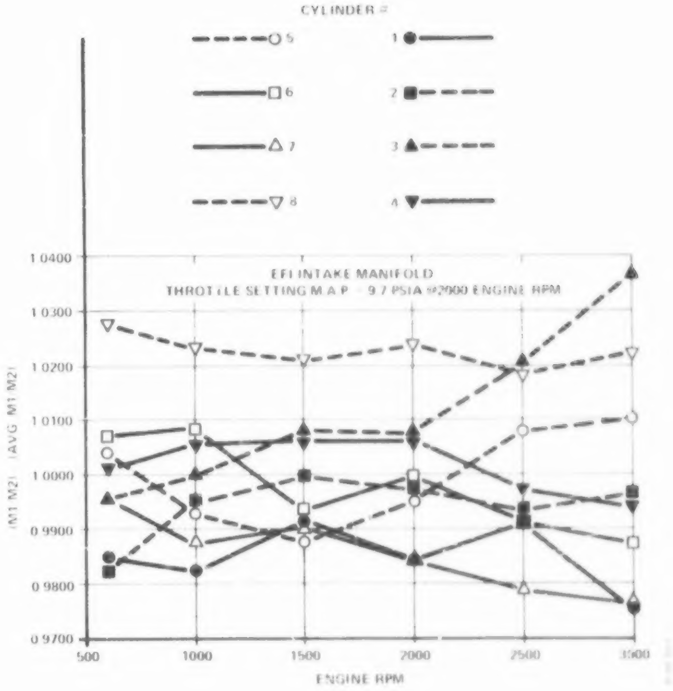

Figure B-7 - Effect of Speed on Cylinder Mass Air Flow
1970 Ford 429 C.I.D. Engine
E.F.I. Intake Manifold

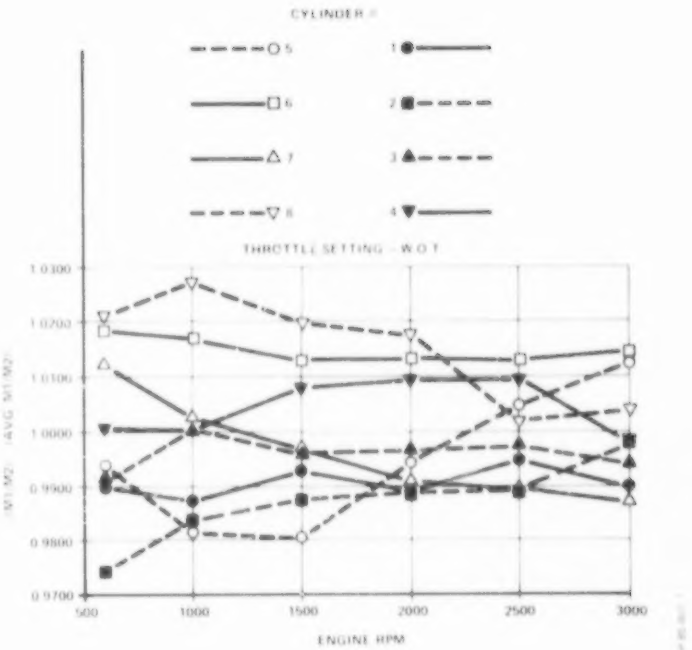

Figure B-8 - Effect of Speed on Cylinder Mass Air Flow
1970 Ford 429 C.I.D. Engine
E.F.I. Intake Manifold

To further see if the intake manifold favored one cylinder over the others, at all the operating conditions, Figure B-9 was plotted. The normalized ratio $[(M_1/M_2 \div (\text{Avg. } M_1/M_2)]$ was plotted at three speeds for each cylinder. Of course, the deviation is still 4 percent, but it seems as if cylinders 1, 2, and 7 receive less air mass compared to other cylinders due to the intake manifold.

Rather than pursue further evaluations of air flow as it is influenced by the intake manifold, it was decided to evaluate air/fuel ratio from each cylinder using exhaust gas analysis. To perform this task, the intake manifold was equipped with a set of matched fuel injectors (all flow within about a 1 percent range) and the exhaust manifolds were provided with eight exhaust sampling probes running into the cylinder heads, extending about one inch from the plane of the manifold and head interface into the exhaust channels. Care was taken to locate each probe in the same relationship to the exhaust valves. To measure CO and CO_2, Beckman NDIR analyzers were used. To measure the total hydrocarbons in the exhaust, a Beckman FID Model 400 was used. Oxygen in the exhaust was measured using a Beckman oxygen sensor, Model 715. The Spindt method* was used to compute the air/fuel ratios and the results are shown in Figures B-10 through B-12.

For idle conditions (Figure B-10) two average air/fuel ratios were evaluated. At an average air/fuel ratio of 15.7:1, the total variation between the cylinders was about 6 percent. For an air/fuel ratio of 14.6:1 the total variation was only 2.7 percent.

Figure B-11 shows data at 1200 rpm for two values of brake torque. At 45 ft-lb, the average air/fuel ratio was 17.84:1 and the spread between cylinders was 0.8 ratio or 4.5 percent of the average. For a torque of 100 ft-lb, the average air/fuel ratio was 19.6:1 and the spread between cylinders was 1.0 ratio or about 5.1 percent of the average.

Figure B-12 shows data at 2000 rpm for two values of brake torque. At 70 ft-lb the average air/fuel ratio was 18.82:1 and the spread between cylinders was 1.28 ratios or 6.8 percent of the average. At 180 ft-lb of torque the average air/fuel ratio was 19.29:1 and the spread between cylinders was 1.64 ratios or 8.5 percent of the average.

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*SAE Paper 650507 "Air/Fuel Ratios from Exhaust Gas Analysis," R. S. Spindt.

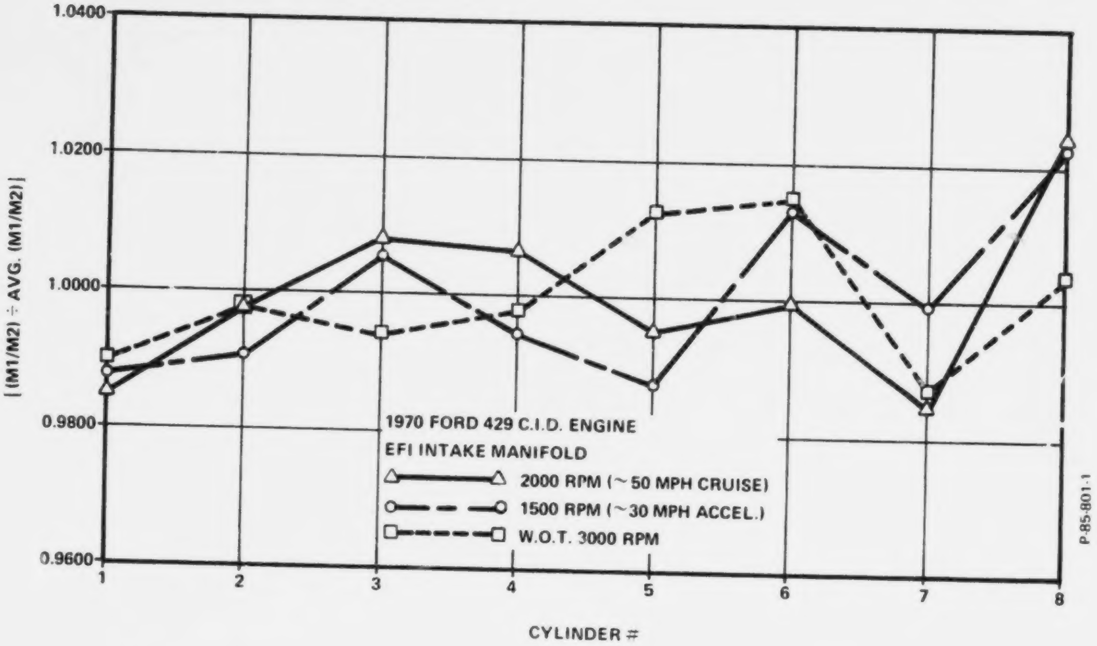

Figure B-9 Intake Manifold Air Distribution Variation
1970 Ford 429 C.I.D. Engine
E.F.I. Intake Manifold

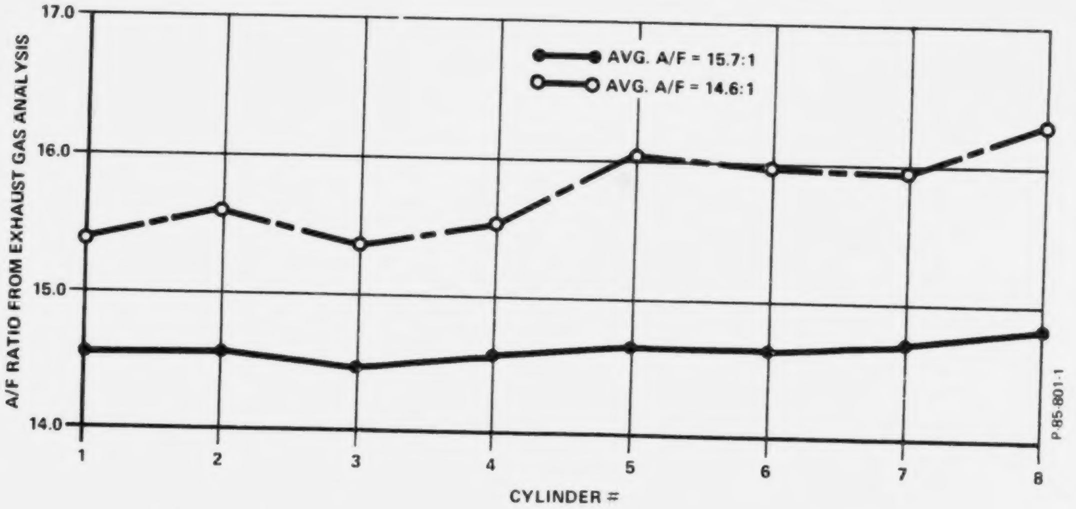

Figure B-10 - Air/Fuel Ratio Variation at Idle
1970 Ford 429 C.I.D. Engine
E.F.I. Manifold with Matched Injectors - Group Injection
Standard Exhaust System

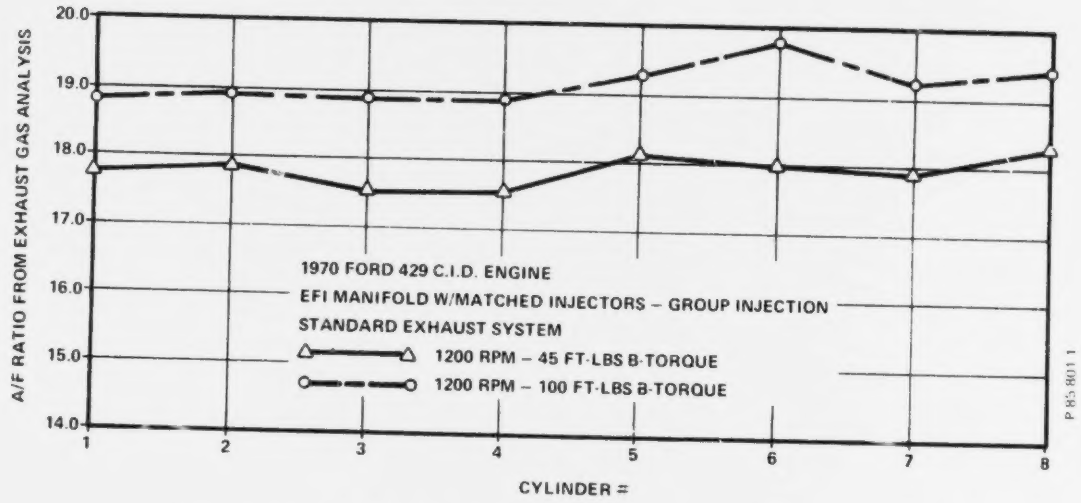

Figure B-11 - Air/Fuel Ratio Variation at 30 MPH
1970 Ford 429 C.I.D. Engine

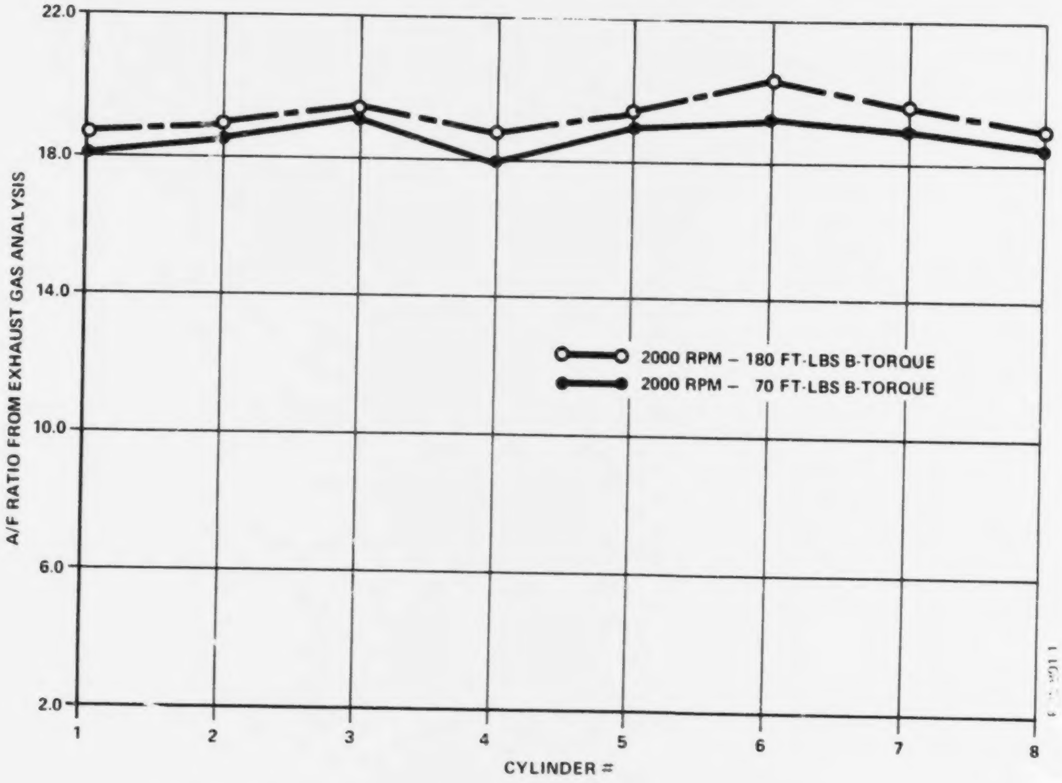

Figure B-12 - Air/Fuel Ratio Variation at 50 MPH

Although the results seem inconsistent as regards lean or rich cylinders at all conditions, certain trends are apparent. From Figure B-11 (1200 rpm) cylinders 1, 2, 3, and 4 (right bank) were at relatively rich A/F ratios as compared to the other four cylinders. Similarly, the data for 2000 rpm (Figure B-12) show that cylinders 1, 2, 4, and 8 operated at relatively richer conditions than did cylinders 3, 5, 6, and 7.

To summarize and correlate all of the results, Table B-1 was prepared. This tabulates the key parameters versus conditions for the three types of tests performed; namely, cylinder peak pressure, the ratio M_1/M_2 for intake manifold evaluation, and air/fuel ratio.

Except for idle conditions, the intake manifold appears to contribute a 4 percent non-uniformity between cylinders to the mass air flow. At idle the non-uniformity is more than 10 percent. No special data were taken to help determine why the variation was so great at idle; therefore, its cause can only be theorized. Two unusual conditions may be responsible. First, the flow across the throttle plates is sonic because the manifold absolute pressure is less than half of an atmosphere. This can create shock waves that might influence flow streams. Second, the projected flow areas with the throttle closed are shaped like very narrow crescents that could cause peculiar flow eddies below the plates that would influence the flow streams.

One might also consider that the wide variation is due to the low charge density that results from a M.A.P. of 6.3 psia. However, note that Figure B-5 indicates reduced variation with speed at a fixed throttle setting. M.A.P. data at the higher speeds are not available but the pressure would be considerably lower. Similarly, the 1200 and 2000 rpm data show no trends indicative of charge density effects.

The air/fuel ratio percentage variations (+ and - about the average) are the result of contributions from the engine pumping variations, the intake and exhaust manifolds and the fuel injection system. The combined effect of the intake manifold and the engine is represented by the peak cylinder pressure variations shown in Figures B-13, B-14, and B-15 for idle (600 rpm), 1200 rpm, and 2000 rpm, respectively. The calculated total percentage variations are tabulated in Table B-1 for the data shown on these figures. The fuel injection system was matched (for grouped injection) to provide about a 1 percent total variation was 6.3 percent; therefore, as much as a 7.3 percent variation could be expected in air/fuel ratio. Actually, it was much less for richer average air/fuel ratio, but

Table B-1 - Summary of Results

ENGINE SPEED RPM	BRAKE TORQUE LB-FT	FIGURE NUMBER	CONDITIONS						TOTAL (+ AND -)% VARIATION		
			MOTORED	OPERATING	MANIFOLDS		"VEHICLE" CONDITION	OTHER	A/F RATIO	$\frac{M_1/M_2}{\text{AVG. } M_1/M_2}$	PEAK CYL. PRESSURE
					INTAKE	EXHAUST					
600	---	3	●				Idle	---	---	--	5.4
↓	---	13	●		●		↓	6.3 psia M.A.P.	---		6.3
	---	5	●		●			6.3 psia M.A.P. at 600 rpm	---	10.5%	--
640	35	10		●	●	S'td.		Avg. A/F Ratio = 14.6:1	2.7	---	--
640	35	10		●	●	S'td.		Avg. A/F Ratio = 15.7:1	6.0	---	--
1200	---	3	●				30 mph	---	---	---	5.4
↓	---	14	●		●		↓	10.5 psia M.A.P.	---	---	4.6
	---	6	●		●			10.5 psia M.A.P.	---	4	--
	45	11		●	●	S'td.	30 mph Cruise	Grouped Injection	4.5	---	--
	100	11		●	●	S'td.	↓ Accel.	Grouped Injection	5.1	---	--
	45	16		●	●	Tuned	Cruise	Sequential Injection	12.05	---	--
	100	16		●	●	Tuned	Accel.	↓	8.4	---	--
	45	18		●	●	S'td.	Cruise		12.0	---	--
	100	18		●	●	S'td.	Accel.		7.4	---	---
2000	---	3	●				50 mph	---	---	---	4.25
↓	---	15	●		●			9.7 psia M.A.P.	---	---	4.65
	---	7	●		●			9.7 psia M.A.P.	---	4	--
	70	12		●	●	S'td.	50 mph Cruise	Grouped Injection	6.8	---	--
	180	12		●	●	S'td.	↓ Accel.	Grouped Injection	8.5	---	--
	70	17		●	●	Tuned	Cruise	Sequential Injection	13.6	---	--
	180	17		●	●	Tuned	Accel.	↓	7.0	---	--
	70	19		●	●	S'td.	Cruise		16.5	---	--
	180	19		●	●	S'td.	Accel.		5.5	---	--
300	---	--	●		●	S'td.	---	Compression Test	---	---	7.8

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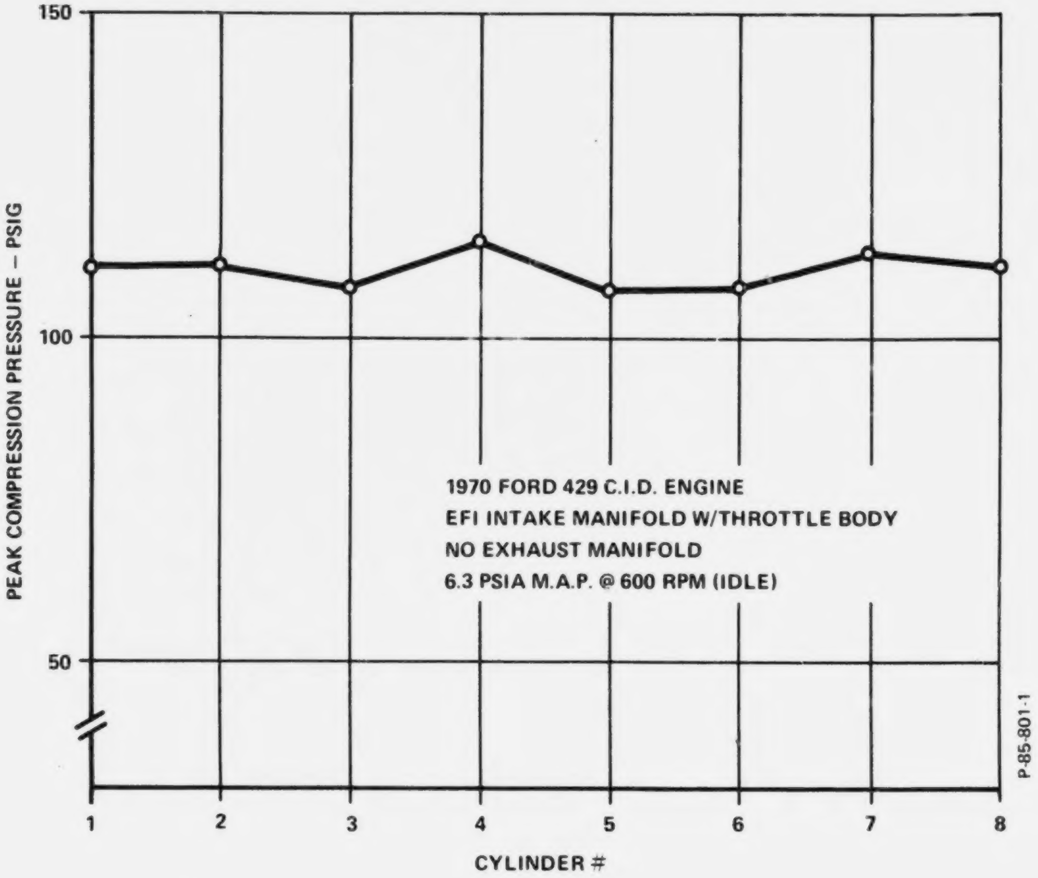

Figure B-13 - Air/Flow Variation at 600 RPM

was 6 percent at an air/fuel ratio of 15.7:1. At 1200 rpm, the sum of the pressure and fuel flow variation was about 5.6 percent as compared to an air/fuel ratio variation of 4.5 to 5.1 percent. At 2000 rpm, the sum of the pressure and fuel flow variation was about 5.7 percent and the air/fuel ratio variation was between 7 and 8.5 percent.

Although the correlation is not exact, it is reasonable. Other effects can account for the differences. These would include effects from the exhaust manifolds, the higher gas temperatures and random

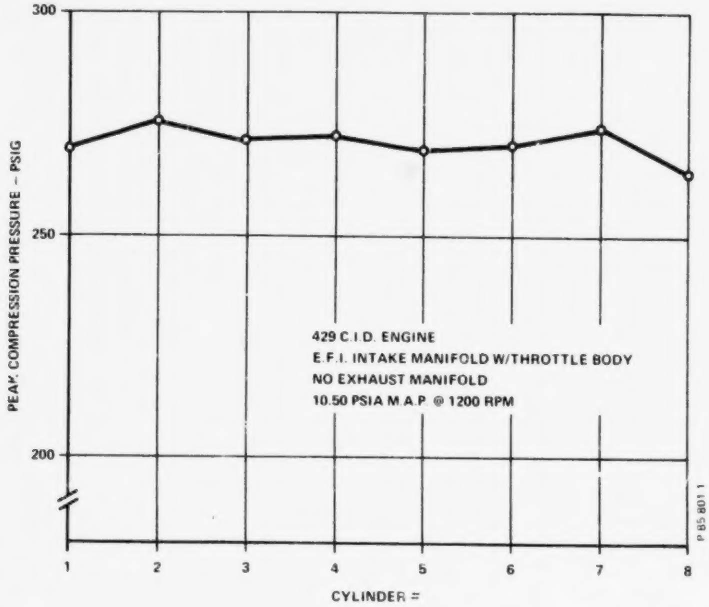

Figure B-14 - Air/Flow Variation at 1200 RPM

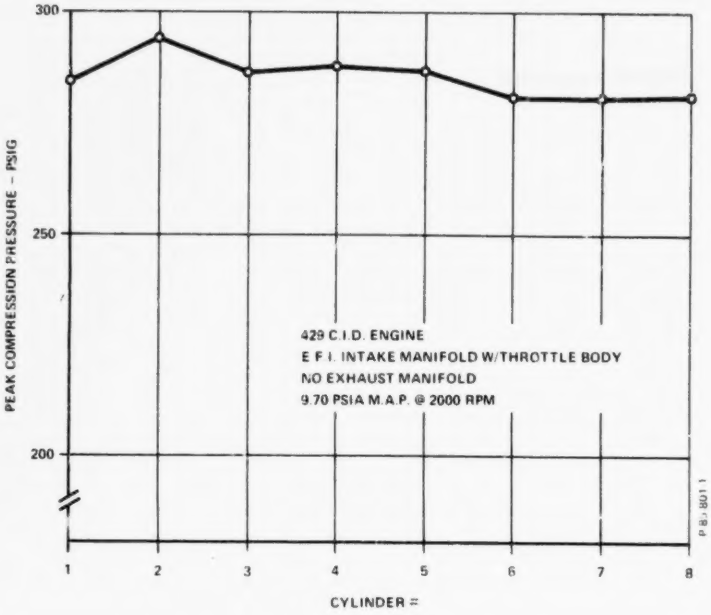

Figure B-15 - Air/Flow Variation at 2000 RPM cancellations or reinforcements between low or high peak pressures for a given cylinder and high or low fuel delivery rates of the corresponding fuel injectors.

In the tests discussed above, group injection was used when air/fuel ratio measurements were made and this may have had some influence on the variation in the air/fuel mixture from one cylinder to another. In group injection, cylinders 1, 4, 5, and 8 are injected simultaneously followed by one crank revolution later by simultaneous injection of cylinders 2, 3, 6, and 7. Therefore, when the first cylinder in a group draws the charge, fuel is still waiting to be drawn into the other three cylinders. This may create a problem of "robbing" some of the fuel injected into the other ports by cylinders that induct the charge first. To verify this possibility, the EFI system was revised to provide individually timed (sequential) injection. Results of this are discussed below.

To recheck the engine condition, cylinder compression checks were made using standard automotive diagnostic equipment. The compression checking gauge was adapted to thread into the spark plug port. To measure the cylinder compression, all the spark plugs were removed and the engine was motored at 300 rpm with the throttle wide open (all manifolds installed). The results are summarized below:

Cylinder Number	Compression
1	190
2	195
3	185
4	190
5	195
6	200
7	195
8	195

The cylinder compression varied from a low of 185 psig to a high of 200 psig. The average pressure was 193 psig and the total variation was 7.8 percent. These variations in the compression values are considered normal, and the engine was judged to be in good condition.

Two additional test series were run to evaluate any improvements resulting from using sequential fuel injection and the pressure pulse isolation provided by a tuned exhaust manifold.

To evaluate the effect of sequential injection, tests were run both with the tuned exhaust headers (Figures B-16 and B-17) and with the standard exhaust manifolds (Figures B-18 and B-19). To keep the back pressure to a minimum, the headers were used without any mufflers or resonators, whereas the standard manifolds were used with a complete exhaust system. The injection timing was adjusted to commence injection 50 degrees before the intake valve opens. With the 429 C.I.D. engine valve timing, this allowed the fuel injection to take place when both the intake and the exhaust valves were closed. For both exhaust systems, the tests were run at the same speed, torque and ignition timing. An attempt was made to set the same air/fuel ratio also. Exhaust emissions were measured from each cylinder to compute the air/fuel ratios. The results are summarized in Table B-2.

The results indicate that the exhaust system exerts very little influence upon the variation of air/fuel ratio between cylinders. It is of interest to note that the spread is a little greater at the high torque points when the tuned headers are installed.

These tests, using sequential injection, resulted in higher percentage variations in air/fuel ratios - particularly at the low torque set points. This was believed to be due to the method used to adjust the control unit.

As a standard procedure, pulse durations from the experimental sequential injection control box to the individual injectors were matched at a 3 millisecond pulse width to within 5 microseconds (0.17 percent). At 1200 rpm, 100 ft-lb torque and 2000 rpm 180 ft-lb torque set points, the injection pulse period was in the vicinity of 3 milliseconds; however, for the test points of 1200 rpm, 45 ft-lb torque and 2000 rpm, 70 ft-lb torque the injection pulse period was only half as much. Also, the experimental control unit did not maintain the 5 microsecond tolerance on injector pulse widths for the lower power set points. This is probably the reason for higher air/fuel ratio variations at these test points. Since the object of these tests was to evaluate the exhaust manifolds, there was no attempt made to match pulse durations at the lower power set points.

To minimize the air/fuel variations with the sequential injection for the parametric tests, the plus durations for all eight cylinders were adjusted such that the maximum cylinder to cylinder air/fuel ratio variation was no greater than that with group injection. The adjustments were made at all the power settings.

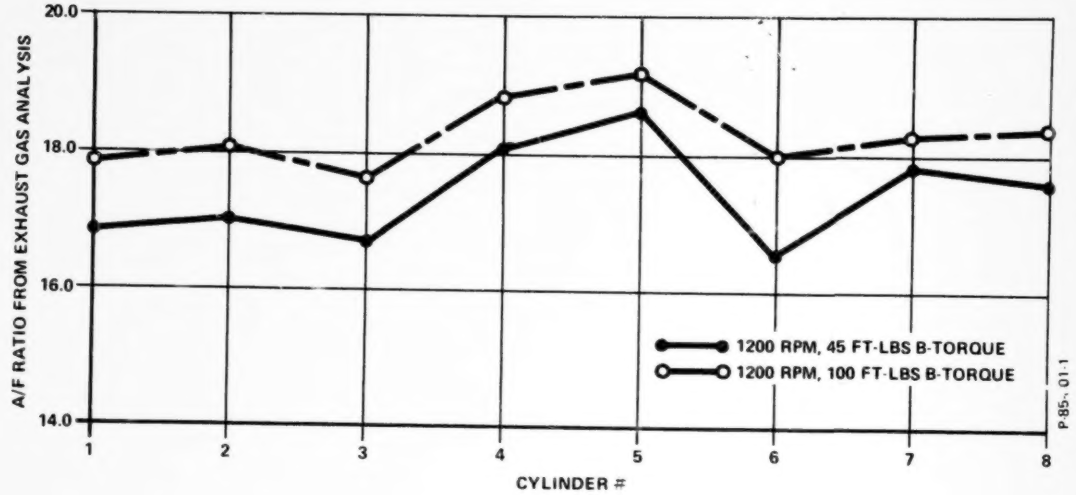

Figure B-16 - Air/Fuel Ratio Variation at 1200 RPM
1970 Ford 429 C.I.D. Engine
E.F.I. Manifold with Matched Injectors - Sequential Injection
Tuned Exhaust Manifolds - No Mufflers

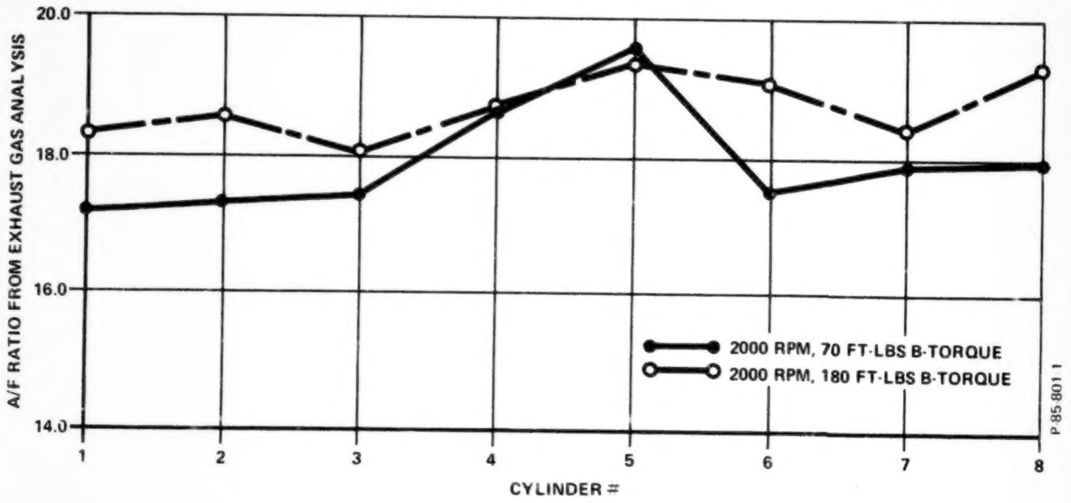

Figure B-17 - Air/Fuel Ratio Variation at 2000 RPM
1970 Ford 429 C.I.D. Engine
E.F.I. Manifold with Matched Injectors - Sequential Injection
Tuned Exhaust Manifolds - No Mufflers

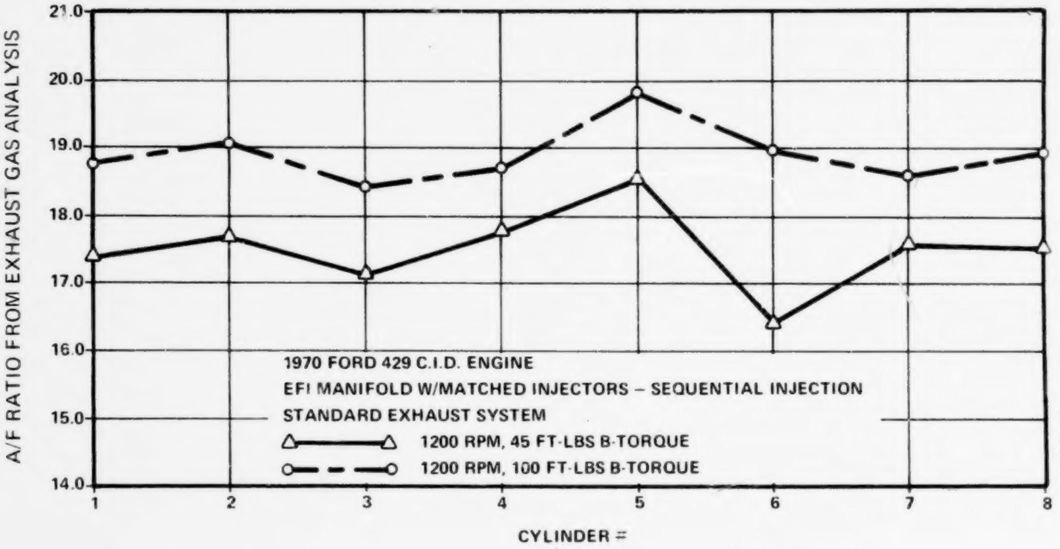

Figure B-18 - Air/Fuel Ratio Variation at 1200 RPM
1970 Ford 429 C.I.D. Engine

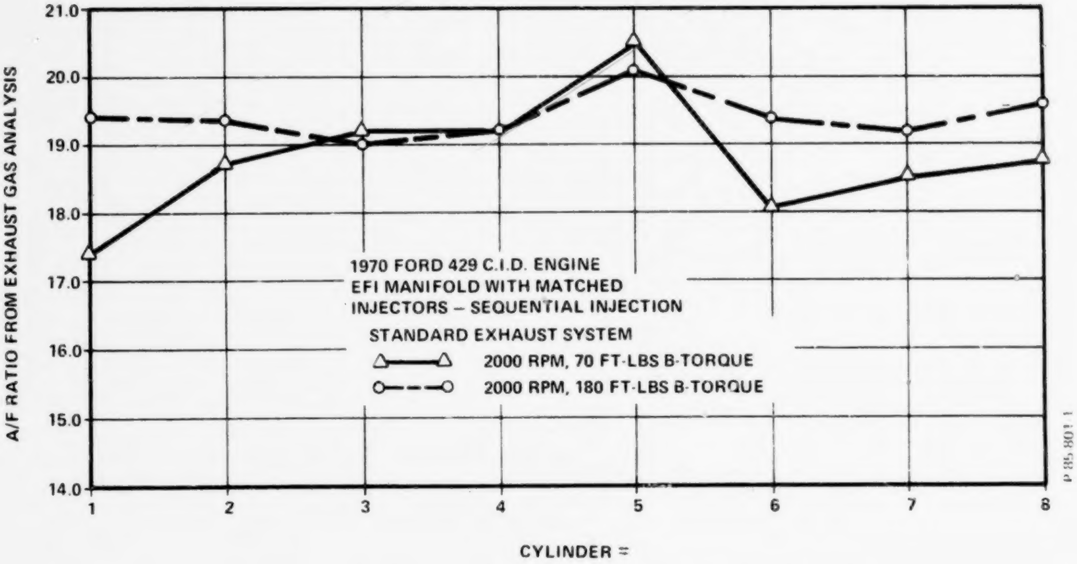

Figure B-19 - Air/Fuel Ratio Variation at 2000 RPM
1970 Ford 420 C.I.D. Engine

Table B-2 - Exhaust System Effects on A/F Ratio

TUNED EXHAUST HEADERS

Test Condition		
RPM	Brake-Torque (ft-lbs)	Total Variation of A/F Ratio - %
1200	45	12.05
1200	100	8.4
2000	70	13.6
2000	180	7.0

STANDARD EXHAUST SYSTEM

Test Condition		
RPM	Brake-Torque (ft-lbs)	Total Variation of A/F Ratio - %
1200	45	12.0
1200	100	7.4
2000	70	16.5
2000	180	5.5

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APPENDIX C

BASELINE EVALUATIONS OF THE 429 C.I.D. FORD ENGINE WITH BENDIX EFI SYSTEM CALIBRATED FOR ULTRA-LEAN OPERATION

C.1 INTRODUCTION

The Ford 429 C.I.D. engine, which was dismounted from the leased automobile, was installed and instrumented to perform baseline tests on the engine dynamometer. The baseline data were recorded for the following steady-state operating conditions.

RPM	Brake Torque (ft-lbs)
1200	45
1200	100
2000	70
2000	180
640	35 (Idle)

C.2 SUMMARY

The engine was operated at each of the above set points, and the following parameters were recorded. Indolene clear (non-leaded) was used throughout the test.

- air flow
- fuel-air ratio
- brake torque
- inlet air temperature
- exhaust gas temperature
- water out temperature
- fuel flow
- barometric pressure
- M.A.P. (Manifold Absolute Pressure)
- oil temperature
- injector pulse width
- dry and wet bulb temperatures

The exhaust emissions data were recorded on the Texas Instrument recorder.

The standard EFI (Electronic Fuel Injection) spark advance and the standard spark plug gap of 0.035 in. were used for the baseline tests. The ignition timing, spark duration and the intensity of spark are summarized in the following table:

Engine RPM	Brake Torque (ft-lbs)	Ignition Timing (°BTDC)	Spark Duration (msec)	Spark Intensity (KV)
1200	45	12	1.39	13
1200	100	13	1.39	13
2000	70	37	1.0	8
2000	180	37	0.833	9
640	35	6	3.03	11

When the standard EFI system group injection is used, cylinder numbers 2, 6, 3 and 7 belong to Group 2 and cylinder numbers 8, 1, 5 and 4 belong to Group 1. Groups 1 and 2 inject 120° BTDC on cylinders 8 and 2, respectively. Group 2 is synchronized to inject when spark plug No. 8 fires, and Group 1 is synchronized to inject when spark plug No. 2 fires (with ignition timing set at TDC).

The recorded data were reduced using the computer. The air/fuel ratio was measured as well as computed from the exhaust **emissions**. The exhaust emissions were computed on a concentration as well as on a mass (gms/bhp-hr) basis. The emissions data on a concentration basis include the dilution factor.

SUMMARY OF THE EMISSIONS RESULTS

			HC		CO		NO_x	
Test No.	Engine RPM	Brake Torque (ft-lbs)	PPM C*	gms/bhp-hr	Percent	gms/bhp-hr	PPM	gms/bhp-hr
1	640 (Idle)	35	2142.85	8.16	1.70	131.21	101.19	1.30
2	1200	45	1089.48	4.72	0.28	25.20	40.35	0.89
3	1200	100	1139.70	2.85	0.28	14.13	70.55	0.59
4	2000	70	1434.93	3.61	0.15	7.99	176.78	1.49
5	2000	180	445.28	0.69	0.30	9.65	456.64	2.40

*parts per million as carbon

C.3 TEST PROCEDURE

The instrumentation consisted of a Flo-Tron linear mass flow meter in conjunction with a Foxboro transmitter to measure actual mass flow rate of the fuel. A Meriam laminar flow meter in conjunction with another Foxboro transmitter was used to measure the air flow. The Flo-Tron electronic circuitry computed the air/fuel ratio from these two signals.

To measure the CO, CO_2, and NO emissions, Beckman NDIR type analyzers were used. To measure the total hydrocarbons in the exhaust, a Beckman FID Model 400 was used. All the emissions were recorded on Texas Instrument recorders. A Beckman oxygen sensor, Model 715, was used to measure the percentage of oxygen present in the exhaust. A magnetic pick-up along with a sixty-tooth sprocket was used to count pulses to read the engine speed in rpm.

After calibration of all the instruments, the engine was started and kept running until the oil and the water temperatures were stabilized. The water temperature was maintained at about 170°F.

After the warm-up, using the dynamometer speed control, the engine rpm was set at the desired value. After setting the speed, using the throttle control on the engine, the desired load was set. The speed was corrected, if necessary. The engine was maintained at this condition and sampling of the exhaust was started. When everything seemed stable, all the data were recorded.

The above procedure was repeated to set other test points and to record the data.

C.4 DISCUSSION OF THE RESULTS

The calibration of the electronic control unit (ECU) for the baseline EFI was set for ultra-lean operation to reduce NO_x emissions. However, because of such a lean operation, engine misfires at certain operating conditions caused hydrocarbon and carbon monoxide emissions to read high.

The attached computer print-outs (Attachment I) show all the parameters recorded at each operating condition along with the emission analysis. The emissions are computed in the units of concentration, gm/hr and gm/bhp-hr. All emissions results in terms of concentration are corrected by the dilution factor.

The air/fuel ratio is computed from the recorded information on the air flow and the fuel flow. The air/fuel ratio is also computed using the emissions data. In most cases the air/fuel ratios computed using the emissions data and measured air and fuel flows agree within one air/fuel ratio. Measured fuel flow might be off as it was difficult to read on the Flo-Tron. This has since been corrected.

Tests 6, 7 and 8 are re-runs of tests 2, 3, and 4 with slightly richer mixtures to eliminate the misfire. These tests were run to obtain additional information on emissions if the mixture is made richer so that there is no misfire.

The computer print-out shows injector timing to be zero. These tests were run with group injection, and the data were hand recorded. In order to use the digital part of the computer, some value for the injection timing had to be used and for simplicity the value given was zero. Similarly, standard EFI ignition calibration was used, setting the ignition timing to 4° btdc at 640 rpm; and, again, to use the program, a value of zero degree was given for all the tests.

C.5 SAMPLE CALCULATIONS

Recorded Data

RPM	Brake Torque (ft-lbs)	Baro. Pressure (psia)	Humidity (grains/lb-dry air)
1200	45	14.5	30

Air Flow (CFM)	Fuel Flow (lb/hr)	Inlet Air Temp. (°F)	%CO	$\%CO_2$	$\%O_2$
69.75	14.5	77	0.206	10.2	6.4

NO (PPM)	FID(HC)(PPM/propane equivalent)
35	260

$$W_a = \text{air flow (lb/hr)} = \text{CFM}\{1 + 0.0033\ (70 - T)\}\ \frac{\text{Baro.Press.}}{14.7} \times 4.52\ \frac{\text{lbs}}{\text{hr-CFM}}$$

where

T = inlet air temperature in. °F

$\{1 + 0.0033(70 - T)\}$ is the temperature correction factor for the laminar flow meter.

$$W_a = 69.75\ \{1 + 0.0033\ (70 - 77)\}\ \frac{14.5}{14.7} \times 4.52$$
$$= 303.79\ \frac{\text{lbs}}{\text{hr}}$$

$$\text{measured air/fuel ratio} = \frac{303.79}{14.5} = \underline{\underline{20.95}}$$

$$NO_c = NO \times K_H \times D.F.$$

where

NO_c = nitric oxide concentrations in ppm

NO = observed nitric oxide concentration in ppm

K_H = humidity correction factor = $\frac{1}{1 - 0.0047\ (H-75)}$

H being grains of moisture per lb. of dry air

$$D.F. = \text{dilution factor} = \frac{14.5}{\%CO_2 + \frac{1}{2}\ \%CO + \frac{3 \times HC}{10{,}000}}$$

$$NO_c = 35 \times .8254 \times 1.3967 = 40.35 \text{ ppm}$$

$$NOX_m = \frac{NO}{10^6} \times V_E \times M_{NO_2} \times CF_\omega{}' \times K_H$$

where

NOX_m = oxides of nitrogen in gms/hr

V_E = exhaust flow (ft^3/hr) = $\frac{W_A + W_F}{P_E}$

W_A = air flow (lbs/hr)
W_F = fuel flow (lbs/hr)
P_E = density of exhaust = 0.075 $\frac{lbs}{ft^3}$

M_{NO_2} = density of NO_2 (gms/ft^3) = 54.16

$CF_\omega{}'$ = water correction factor = 0.913

$$NOX_m = \frac{35}{10^6} \left(\frac{303.79 + 14.5}{.075}\right) 54.16 \times 0.913 \times 0.8254$$

$$NOX_m = 6.06 \frac{gms}{hr}$$

$$CO_c = CO \times D.F.$$

where

CO_c = carbon monoxide concentration in percent
CO = observed carbon monoxide concentration in percent
D.F. = dilution factor

$$CO_c = .206 \times 1.3967 = 0.2877\%$$

$$CO_m = \frac{CO}{100} \times V_E \times M_{CO} \times CF_\omega$$

where

CO_m = carbon monoxide in gms/hr

V_E = exhaust volume (ft^3/hr)

M_{CO} = density of CO = 32.97 $\frac{gms}{ft^3}$

CF_ω = water correction factor = 0.8991

$$CO_m = (\frac{.206}{100}) (\frac{318.29}{.075}) 32.97 \times 0.8991 = 259.0 \frac{gms}{hr}$$

$$HC_c = HC \times 3 \times D.F.$$

where

HC_c = total hydrocarbon concentration in ppm - carbon equivalent

HC = observed hydrocarbon propane equivalent in ppm

$$HC_c = 260 \times 1.3967 \times 3 = 1089.42 \text{ ppm C}$$

$$HC_m = 3 \times \frac{HC}{10^6} \times V_E \times M_{HC} \times CF_\omega$$

where

HC_m = total hydrocarbons in gms/hr

M_{HC} = density of HC = 16.33 $\frac{gms}{ft^3}$

$$HC_m = \frac{3 \times 260}{10^6} \times 4243.86 \times 16.33 \times .8991 = 48.6 \frac{gms}{hr}$$

$$\text{Brake Horsepower} = \frac{\text{Brake Torque x rpm}}{5252}$$

$$= \frac{45 \times 1200}{5252} = 10.28$$

$$\text{BSFC} = \frac{W_F}{\text{B.H.P.}} = \frac{14.5}{10.28} = 1.41$$

Emissions in gms/bhp-hr:

$$HC_{mh} = \frac{48.6}{10.28} = 4.72 \ \frac{\text{gms}}{\text{bhp-hr}}$$

$$CO_{mh} = \frac{259}{10.28} = 25.2 \ \frac{\text{gms}}{\text{bhp-hr}}$$

$$NOX_{mh} = \frac{6.06}{10.28} = 0.588 \ \frac{\text{gms}}{\text{bhp-hr}}$$

Air/Fuel Ratio from the Exhaust Components

$$(A/F)_e = F_b \{11.492 \ F_c \left(\frac{1 + E/2 + D}{1 + E}\right) + \frac{120 \ (1 - F_c)}{3.5 + E}\}^{*}$$

where

$(A/F)_e$ = A/F from exhaust analysis

$$F_b = \frac{\%CO + \%CO_2}{\%CO + \%CO_2 + \frac{3 \times HC}{10{,}000}}$$

F_e = fraction of carbon in fuel = 0.867

$$E = \frac{\%CO}{\%CO_2}$$

$$D = \frac{\%O_2}{\%CO_2}$$

---

*"Air/Fuel Ratios from Exhaust Gas Analysis," R. S. Spindt, SAE Paper 650507

$$(A/F)_e = .9925 \{9.9635 (\frac{1 + .01 + .6274}{1.0201}) + \frac{15.96}{3.5201}\}$$

$$(A/F)_e = 20.37$$

ATTACHMENT I
COMPUTER PRINT-OUTS OF BASELINE EMISSION DATA

```
                       ***** EPA PARAMETRIC TEST *****

              DATE  4/30/71                          TEST   1

SPEED (RPM) =  640.0                         BRAKE TORQUE (FT-LB) =       35.000

IGNITION TIMING (DEGREES BTDC) =     6.0     INJECTOR TIMING (DEGREES BTDC) =     0.0

AIR FLOW (LB/HR) =      84.287               FUEL FLOW (LB/HR) =       6.200

POWER (BRAKE HP) =       4.265               INJECTOR PULSE WIDTH (M-SEC) =       3.230

MEASURED AIR/FUEL RATIO =       13.595       BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =       1.45

INLET AIR TEMPERATURE (DEGREES-F) =    80.0  EXHAUST GAS TEMPERATURE (DEGREES-F) =       0.000

OIL TEMPERATURE (DEGREES-F) =       0.000    WATER-OUT TEMPATURE (DEGREES-F) =       0.000

MANIFOLD ABSOLUTE PRESSURE (PSIA) =       5.500   BAROMETRIC PRESSURE (PSIA) =      14.500

EXHAUST BACK PRESSURE (IN-WATWR) =       0.000    RELATIVE HUMIDITY (GRAINS) =      30.000

                          EMISSION DILUTION FACTOR =       1.066


                                 EMISSION ANALYSIS

NO (PPM) =    115.0000             NO (GM/HR) =  0.55657E+01          NO (GM/BHP-HR) =  0.13049E+01
NO CORRECTED (PPM) =    101.1980

CO (%) =      1.7058               CO (GM/HR) =  0.55963E+03          CO (GM/BHP-HR) =  0.13121E+03

CO2 (%) =     13.4328

HC (PPM C) =  2142.8569            HC (GM/HR) =  0.34821E+02          HC (GM/BHP-HR) =  0.81643E+01

O2 (%) =      2.2000

                      CALCULATED AIR/FUEL RATIO =      15.132
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                                ***** EPA PARAMETRIC TEST *****

                       DATE  4/30/71                               TEST   2

    SPEED (RPM) = 1200.0                                  BRAKE TØRQUE (FT-LB) =      45.000

    IGNITIØN TIMING (DEGREES BTDC) =   12.0               INJECTØR TIMING (DEGREES BTDC) =    0.0

    AIR FLØW (LB/HR) =     303.796                        FUEL FLØW (LB/HR) =     14.500

    PØWER (BRAKE HP) =     10.282                         INJECTØR PULSE WIDTH (M-SEC) =      4.030

    MEASURED AIR/FUEL RATIØ =      20.951                 BRAKE SPECIFIC FUEL CØNSUMPTIØN (LB/BHP-HR) =      1.4

    INLET AIR TEMPERATURE (DEGREES-F) =   77.0            EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

    ØIL TEMPERATURE (DEGREES-F) =      0.000              WATER-ØUT TEMPATURE (DEGREES-F) =      0.000

    MANIFØLD ABSØLUTE PRESSURE (PSIA) =       8.550       BARØMETRIC PRESSURE (PSIA) =     14.500

    EXHAUST BACK PRESSURE (IN-WATWR) =       0.000        RELATIVE HUMIDITY (GRAINS) =     30.000

                              EMISSIØN DILUTIØN FACTØR =      1.397


                                       EMISSIØN ANALYSIS

 NØ (PPM) =     35.0000                 NØ (GM/HR) =  0.60627E+01              NØ (GM/BHP-HR) =  0.58965E+00
 NØ CØRRECTED (PPM) =     40.3528

 CØ (%) =      0.2877                   CØ (GM/HR) =  0.25916E+03              CØ (GM/BHP-HR) =  0.25205E+02

 CØ2 (%) =    14.2472

 HC (PPM C) =  1089.4893                HC (GM/HR) =  0.48602E+02              HC (GM/BHP-HR) =  0.47270E+01

 Ø2 (%) =      6.4000

                          CALCULATED AIR/FUEL RATIØ =      20.374
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                                  ***** EPA PARAMETRIC TEST *****

                    DATE  4/30/71                              TEST   3

     SPEED (RPM) = 1200.0                             BRAKE TORQUE (FT-LB) =    100.000

     IGNITION TIMING (DEGREES BTDC) =   13.0          INJECTOR TIMING (DEGREES BTDC) =    0.0

     AIR FLOW (LB/HR) =    378.898                    FUEL FLOW (LB/HR) =     17.700

     POWER (BRAKE HP) =     22.848                    INJECTOR PULSE WIDTH (M-SEC) =      4.930

     MEASURED AIR/FUEL RATIO =     21.407             BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =      0.7

     INLET AIR TEMPERATURE (DEGREES-F) =   76.0       EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

     OIL TEMPERATURE (DEGREES-F) =      0.000         WATER-OUT TEMPATURE (DEGREES-F) =      0.000

     MANIFOLD ABSOLUTE PRESSURE (PSIA) =     10.450   BAROMETRIC PRESSURE (PSIA) =     14.500

     EXHAUST BACK PRESSURE (IN-WATER) =      0.000    RELATIVE HUMIDITY (GRAINS) =     30.000

                              EMISSION DILUTION FACTOR =      1.357


                                    EMISSION ANALYSIS

 NO (PPM) =     63.0000              NO (GM/HR) =  0.13597E+02           NO (GM/BHP-HR) =  0.59511E+00
 NO CORRECTED (PPM) =     70.5553

 CO (%) =      0.2795                CO (GM/HR) =  0.32291E+03           CO (GM/BHP-HR) =  0.14133E+02

 CO2 (%) =     14.2463

 HC (PPM C) =  1139.7019             HC (GM/HR) =  0.65217E+02           HC (GM/BHP-HR) =  0.28543E+01

 O2 (%) =      6.3000

                       CALCULATED AIR/FUEL RATIO =     20.108
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                              ***** EPA PARAMETRIC TEST *****

                   DATE  4/30/71                                   TEST   4

       SPEED (RPM) = 2000.0                             BRAKE TORQUE (FT-LB) =      70.000

       IGNITION TIMING (DEGREES BTDC) =   37.0          INJECTOR TIMING (DEGREES BTDC) =     0.0

       AIR FLOW (LB/HR) =     464.621                   FUEL FLOW (LB/HR) =      21.300

       POWER (BRAKE HP) =      26.657                   INJECTOR PULSE WIDTH (M-SEC) =      3.710

       MEASURED AIR/FUEL RATIO =      21.813            BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =       0.7

       INLET AIR TEMPERATURE (DEGREES-F) =    79.0      EXHAUST GAS TEMPERATURE (DEGREES-F) =       0.000

       OIL TEMPERATURE (DEGREES-F) =       0.000        WATER-OUT TEMPATURE (DEGREES-F) =       0.000

       MANIFOLD ABSOLUTE PRESSURE (PSIA) =       7.750  BAROMETRIC PRESSURE (PSIA) =      14.500

       EXHAUST BACK PRESSURE (IN-WATWR) =       0.000   RELATIVE HUMIDITY (GRAINS) =      30.000

                              EMISSION DILUTION FACTOR =       1.428



                                     EMISSION ANALYSIS

   NO (PPM) =     150.0000                NO (GM/HR) =  0.39927E+02             NO (GM/BHP-HR) =  0.14978E+01
   NO CORRECTED (PPM) =     176.7806

   CO (%) =       0.1571                  CO (GM/HR) =  0.21305E+03             CO (GM/BHP-HR) =  0.79924E+01

   CO2 (%) =     14.2780

   HC (PPM C) =  1434.9360                HC (GM/HR) =  0.96409E+02             HC (GM/BHP-HR) =  0.36167E+01

   O2 (%) =       6.4000

                          CALCULATED AIR/FUEL RATIO =      20.558
```

```
                    ***** EPA PARAMETRIC TEST *****

         DATE  4/30/71                                TEST   5

   SPEED (RPM) = 2000.0                        BRAKE TORQUE (FT-LB) =    180.000

   IGNITION TIMING (DEGREES BTDC) =   37.0     INJECTOR TIMING (DEGREES BTDC) =    0.0

   AIR FLOW (LB/HR) =    702.239               FUEL FLOW (LB/HR) =     32.600

   POWER (BRAKE HP) =     68.545               INJECTOR PULSE WIDTH (M-SEC) =      5.540

   MEASURED AIR/FUEL RATIO =     21.541        BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =      0.4

   INLET AIR TEMPERATURE (DEGREES-F) =   82.0  EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

   OIL TEMPERATURE (DEGREES-F) =      0.000    WATER-OUT TEMPATURE (DEGREES-F) =      0.000

   MANIFOLD ABSOLUTE PRESSURE (PSIA) =      11.250   BAROMETRIC PRESSURE (PSIA) =      14.500

   EXHAUST BACK PRESSURE (IN-WATWR) =      0.000     RELATIVE HUMIDITY (GRAINS) =      30.000

                         EMISSION DILUTION FACTOR =      1.349


                               EMISSION ANALYSIS

NO (PPM) =    410.0000            NO (GM/HR) =  0.16504E+03           NO (GM/BHP-HR) =  0.24077E+01
NO CORRECTED (PPM) =    456.6482

CO (%) =      0.3050              CO (GM/HR) =  0.66194E+03           CO (GM/BHP-HR) =  0.96570E+01

CO2 (%) =     14.3030

HC (PPM C) =    445.2820          HC (GM/HR) =  0.47873E+02           HC (GM/BHP-HR) =  0.69842E+00

O2 (%) =      6.0000

                    CALCULATED AIR/FUEL RATIO =      19.853
```

```
                              ***** EPA PARAMETRIC TEST *****

                    DATE  4/30/71                                   TEST   6

          SPEED (RPM) = 1200.0                          BRAKE TØRQUE (FT-LB) =      45.000

          IGNITIØN TIMING (DEGREES BTDC) =   12.0       INJECTØR TIMING (DEGREES BTDC) =     0.0

          AIR FLØW (LB/HR) =     250.877                FUEL FLØW (LB/HR) =      12.800

          PØWER (BRAKE HP) =      10.282                INJECTØR PULSE WIDTH (M-SEC) =      3.570

          MEASURED AIR/FUEL RATIØ =      19.600         BRAKE SPECIFIC FUEL CØNSUMPTIØN (LB/BHP-HR) =      1.2

          INLET AIR TEMPERATURE (DEGREES-F) =   77.0    EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

          ØIL TEMPERATURE (DEGREES-F) =       0.000     WATER-ØUT TEMPATURE (DEGREES-F) =      0.000

          MANIFØLD ABSØLUTE PRESSURE (PSIA) =      7.350     BARØMETRIC PRESSURE (PSIA) =      14.500

          EXHAUST BACK PRESSURE (IN-WATWR) =      0.000     RELATIVE HUMIDITY (GRAINS) =      30.000

                              EMISSIØN DILUTIØN FACTØR =      1.285


                                    EMISSIØN ANALYSIS

     NØ (PPM) =    62.0000             NØ (GM/HR) =  0.88402E+01            NØ (GM/BHP-HR) =  0.85979E+00
     NØ CØRRECTED (PPM) =     65.7463

     CØ (%) =      0.1610              CØ (GM/HR) =  0.12954E+03            CØ (GM/BHP-HR) =  0.12599E+02

     CØ2 (%) =     14.3887

     HC (PPM C) =   308.3286           HC (GM/HR) =  0.12283E+02            HC (GM/BHP-HR) =  0.11952E+01

     Ø2 (%) =      5.3000

                         CALCULATED AIR/FUEL RATIØ =      19.076
                         ***** EPA PARAMETRIC TEST *****

               DATE  4/30/71                             TEST   7

   SPEED (RPM) = 1200.0                          BRAKE TØRQUE (FT-LB) =    100.000

   IGNITIØN TIMING (DEGREES BTDC) =   30.0       INJECTØR TIMING (DEGREES BTDC) =    0.0

   AIR FLØW (LB/HR) =     345.392                FUEL FLØW (LB/HR) =     17.000

   PØWER (BRAKE HP) =      22.848                INJECTØR PULSE WIDTH (M-SEC) =      4.790

   MEASURED AIR/FUEL RATIØ =     20.317          BRAKE SPECIFIC FUEL CØNSUMPTIØN (LB/BHP-HR) =       0.7

   INLET AIR TEMPERATURE (DEGREES-F) =   77.0    EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

   ØIL TEMPERATURE (DEGREES-F) =      0.000      WATER-ØUT TEMPATURE (DEGREES-F) =      0.000

   MANIFØLD ABSØLUTE PRESSURE (PSIA) =      9.650   BARØMETRIC PRESSURE (PSIA) =     14.500

   EXHAUST BACK PRESSURE (IN-WATWR) =      0.000    RELATIVE HUMIDITY (GRAINS) =     30.000

                        EMISSIØN DILUTIØN FACTØR =      1.306


                              EMISSIØN ANALYSIS

NØ (PPM) =    87.0000               NØ (GM/HR) =  0.17049E+02            NØ (GM/BHP-HR) =  0.74617E+00
NØ CØRRECTED (PPM) =    93.7829

CØ (%) =      0.1946                CØ (GM/HR) =  0.21171E+03            CØ (GM/BHP-HR) =  0.92658E+01

CØ2 (%) =     14.3655

HC (PPM C) =   372.1965             HC (GM/HR) =  0.20057E+02            HC (GM/BHP-HR) =  0.87782E+00

Ø2 (%) =      5.3000

                    CALCULATED AIR/FUEL RATIØ =      19.127
```

```
                              ***** EPA PARAMETRIC TEST *****

                  DATE   4/30/71                                   TEST    8

          SPEED (RPM) = 2000.0                             BRAKE TORQUE (FT-LB) =      70.000

          IGNITION TIMING (DEGREES BTDC) =   30.0          INJECTOR TIMING (DEGREES BTDC) =    0.0

          AIR FLOW (LB/HR) =     405.570                   FUEL FLOW (LB/HR) =     20.300

          POWER (BRAKE HP) =     26.657                    INJECTOR PULSE WIDTH (M-SEC) =      3.560

          MEASURED AIR/FUEL RATIO =      19.979            BRAKE SPECIFIC FUEL CONSUMPTION (LB/BHP-HR) =

          INLET AIR TEMPERATURE (DEGREES-F) =   79.0       EXHAUST GAS TEMPERATURE (DEGREES-F) =      0.000

          OIL TEMPERATURE (DEGREES-F) =      0.000         WATER-OUT TEMPATURE (DEGREES-F) =      0.000

          MANIFOLD ABSOLUTE PRESSURE (PSIA) =      6.900   BAROMETRIC PRESSURE (PSIA) =     14.500

          EXHAUST BACK PRESSURE (IN-WATWR) =      0.000    RELATIVE HUMIDITY (GRAINS) =     30.000

                                      EMISSION DILUTION FACTOR =      1.282


                                          EMISSION ANALYSIS

     NO (PPM) =    265.0000            NO (GM/HR) =  0.61027E+02          NO (GM/BHP-HR) =  0.22894E+01
     NO CORRECTED (PPM) =    280.5090

     CO (%) =      0.2257              CO (GM/HR) =  0.29388E+03          CO (GM/BHP-HR) =  0.11025E+02

     CO2 (%) =     14.3629

     HC (PPM C) =    242.3740          HC (GM/HR) =  0.15631E+02          HC (GM/BHP-HR) =  0.58638E+00

     O2 (%) =      5.1000

                                 CALCULATED AIR/FUEL RATIO =      18.862
*EXIT*
```

APPENDIX D

AUTOMOTIVE IGNITION SPARK ENERGY, VOLTAGE AND CURRENT WAVEFORMS STUDY, PHASE I

D.1 BACKGROUND

A special ignition system was developed several months ago for laboratory use. The system could vary spark duration and energy. It utilized conventional ignition system components which provided easy installation on any conventional IC engine. The basic principal of this ignition system was capacitor discharge method with the added capability of multiple discharges for each ignition period. At the time of its development, one of the most important features desired was a long ignition period, 8 to 10 milliseconds.

Phase I of this study was to determine the spark energy for various control settings of the ignition system as part of an internal research and development study. Control settings were selected to produce waveforms nearest to a continuous spark as possible for one ignition period. Definition of a standard spark gap fixture and testing method was also necessary.

D.2 SUMMARY

The standard spark gap geometry shown in Figure D-1 and oscilloscope voltage and current test method provided an adequate lab testing combination. This setup has been used for years by our Electrical Components Division in Sidney, N. Y. Not all of the engine operating effects on ignition are simulated, namely, arc striking voltage and arc impedance under various air/fuel ratios and engine loads. However, the standard spark fixture provides a uniform and consistent spark gap condition which is vitally needed to discern effects of ignition parameter changes.

The special ignition when operating in the "single SCR mode" will provide an almost continuous current flow during an ignition period thus simulating to high degree the spark produced by the conventional ignition system. Virtually all testing was directed toward this type of operation which severely limited the flexibility of the special system.

The spark "intensity" was defined as the average power dissipated in the arc during the ignition period. In the standard ignition system, this value was 20 watts which remained nearly constant for various battery voltages. However, the spark duration was directly affected, the higher the voltage the longer the spark. Lab tests indicated that a conventional Ford ignition system at a battery voltage of 13 volts had the following characteristics: (1) spark energy of 26.5 millijoules, (2) duration of 1.35 milliseconds, and (3) intensity of 19.6 watts.

The special ignition system can vary duration and energy but not completely independently of each other. For a given duration setting an increase of energy (either by increasing voltage or capacitor value) increases duration simply because the arc impedance decreases with increased current. The special ignition system cannot shut off the current flow during a discharge cycle. The arc behaves as a negative resistance which tends to keep the power dissipated in the arc almost constant. An arc duration within one or two tenths of a millisecond of the desired duration can be set.

The maximum intensity the special ignition system could produce (in the spark gap) was 37 watts with metallic high voltage wire (not normally used). This is almost twice the intensity of the standard ignition system (this intensity includes all other losses such as distributor gap). The energy can be increased almost five-fold by increasing the time duration. (It should be noted that high intensity and long duration will erode electrodes quite quickly since the energy at 6 milliseconds duration could be over 200 millijoules.) The special ignition system has more flexibility at lower intensities; however, the current flow in the spark would be a series of pulses where the time between pulses can be varied.

The spark energies were computed from voltage and current waveform pictures taken from an oscilloscope. The current waveform was presented out of phase for clarity on all pictures taken. The instantaneous product of current and voltage was plotted as a function of time. The area under this curve represented the energy. The major source of error was in translating a voltage from the photo to a number. Some error may exist as a result of rapid changes of voltages where some phase lag would occur between the waveforms representing current and voltage. Some other errors are waveform jitter and oscilloscope amplifier drift. A diode clamping network was needed across the 10 ohm current resistor to keep the high current spike from upsetting the oscilloscope amplifier. This spike was less than 10 microseconds in length. The first 10 to 15 microseconds of each ignition may not be present on the picture due to triggering of the oscilloscope. All of these errors could amount to 10 percent. A more realistic figure would be about 7 percent.

D.3 CONCLUSION

The special ignition system can very closely simulate the standard ignition system in duration, intensity, and energy; however, not in waveform. Sufficient flexibility exists to vary the spark parameters above and below the nominal values. It is possible with metallic high voltage wire to increase intensity to almost twice the conventional system while keeping the duration virtually the same. If energies several times larger than this are desired, the duration must be increased proportionately. One aspect of increasing the energy in the spark was not studied, namely, increasing the spark gap spacing. The arc striking capability of the special ignition system is above 30 K volts which shouldn't restrict increasing the spark plug gap to twice the nominal value. Since the current flow in the arc is governed mostly by the capacitor value and the DC voltage supplied, the increased voltage developed across the larger arc gap would significantly increase the intensity. Further investigation of this area is needed.

D.4 DISCUSSION

One of the most important tools in determining spark gap energy is a gap which will provide a consistent arc at normal atmospheric conditions. Figure D-1 illustrates the three point gap used for producing the arc in this study. The spacing of the two major electrodes was 0.260 inches which produced an arc striking potential of about 11 KV. The static probe induces consistent arc formation but doesn't shunt any energy. Since the points are slightly rounded and become more so after some use, the voltage breakdown value is slightly larger than that shown in the chart of Figure D-1.

Figures D-2 and D-3 illustrate the test setup used to measure spark energy. The high voltage resistance wire and distributor gap simulation used in the test was determined by measuring a Ford ignition system on a typical engine installation. The simulated distributor gap length represents one sample of a new distributor. It would increase with use. The gap used in the test setup was a new spark plug with an electrode spacing of 0.020 inches.

The major losses in a standard ignition system are caused by: (1) induction coil output resistance, (2) high voltage resistance wire, (3) distributor gap. The resistance wire is commonly used to reduce radio frequency interference caused by high surge currents in the voltage distribution wires. The distributor gap losses will vary mostly with spark duration since it appears as a value not related directly to current. The energy difference between Figures D-5 and D-6 is 6.2 millijoules which is caused by the simulated distributor gap. Figure D-4 is a table taken from the "Champion Ignition and Engine Performance Conference, 1970" which indicates a distributor gap loss can be equivalent to the plug gap. It should be noted that values would be different from the setup described here simply because the data in the chart was taken with a plug gap of 0.023 inches. Conventional automotive plug gaps are 0.035 inches. The table also points out that a distributor gap can be a significant loss. Tests have shown that resistance change of 8 K in the high voltage wire produced an energy loss of about 3 millijoules. Resistance losses could account for 10 millijoules in a conventional ignition system. The table in Figure D-4 indicates greater resistance losses but the test setup is not known. The chart is shown here as an example of ignition parameters and associated losses. The peak voltage of the special ignition system was measured with no load and found to be 30 KV. At this voltage the induction coil started to arc through bakelite high voltage tower. During the design of the special ignition system, a limit of 30 KV was set since most automotive coils couldn't handle higher voltages.

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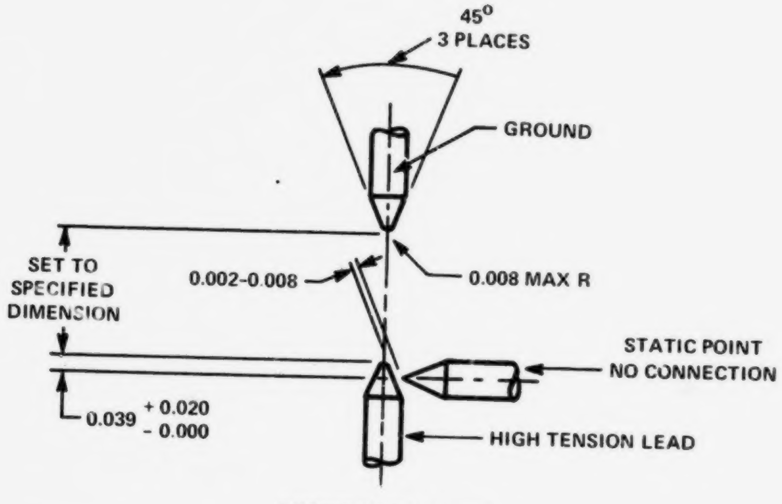
45°
3 PLACES
GROUND
SET TO
SPECIFIED
DIMENSION
0.002-0.008
0.008 MAX R
STATIC POINT
NO CONNECTION
0.039 + 0.020 - 0.000
HIGH TENSION LEAD

3 POINT NEEDLE GAP

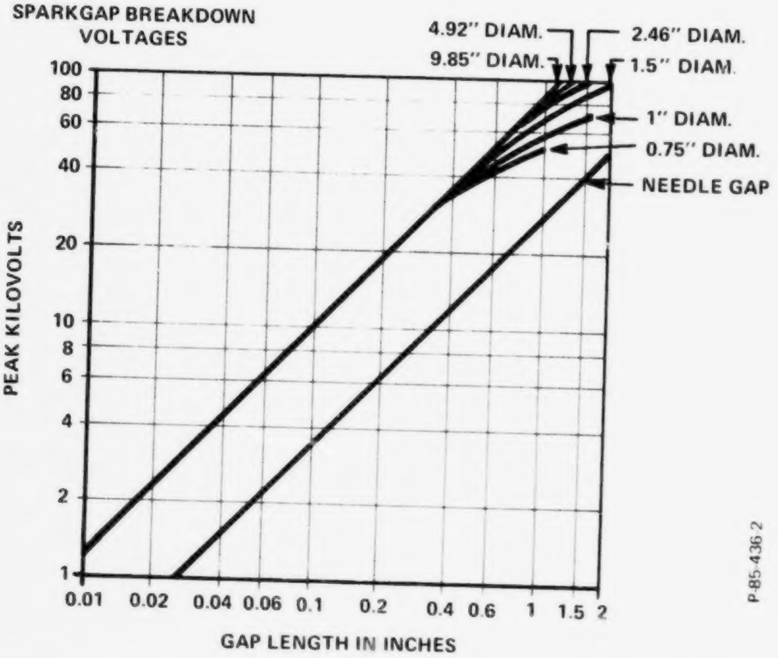

Figure D-1 - Standard Sparkgap Configuration and Sparkgap Breakdown Voltage Chart

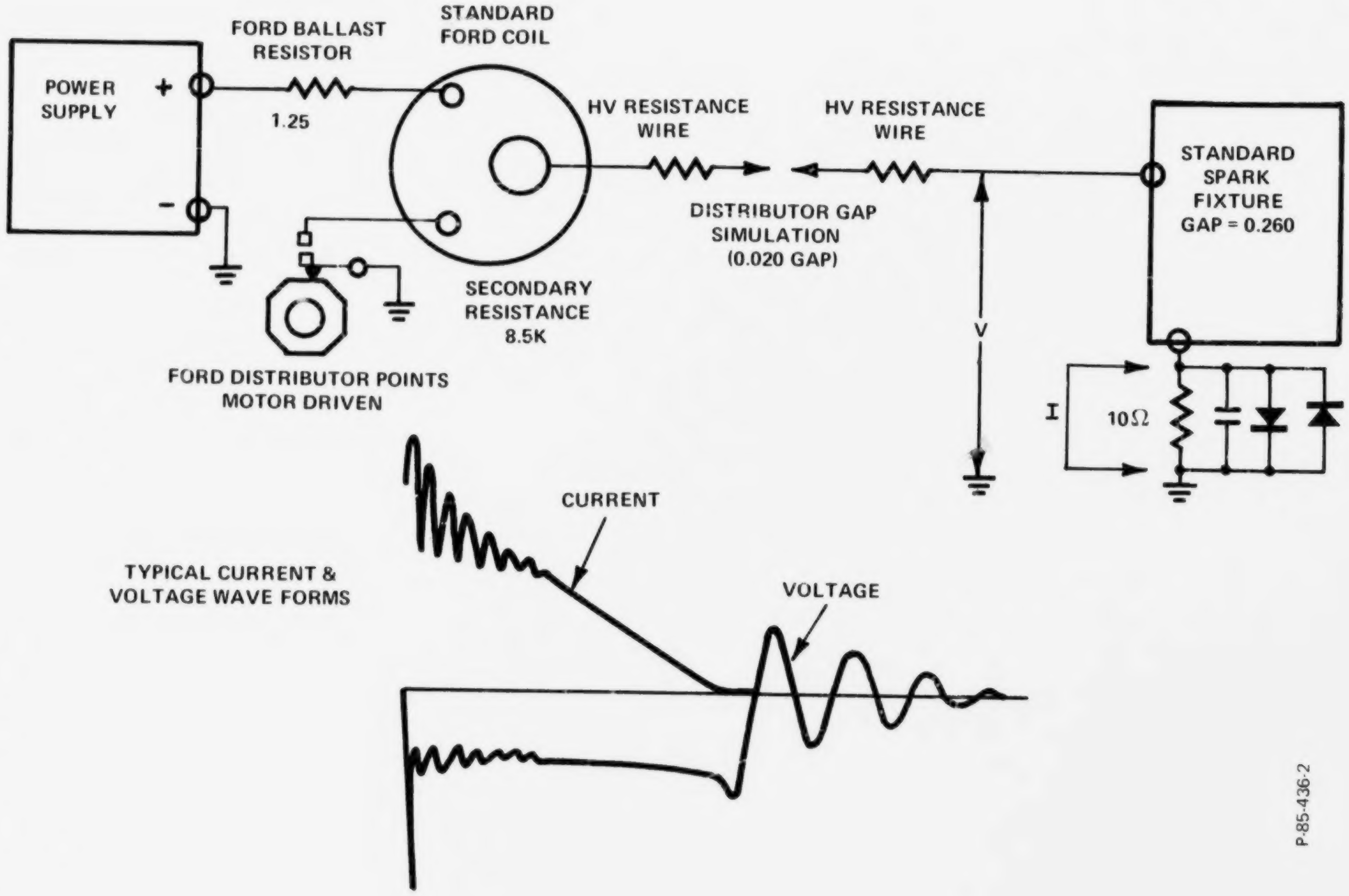
POWER SUPPLY
+
−
FORD BALLAST RESISTOR
1.25
STANDARD FORD COIL
SECONDARY RESISTANCE 8.5K
FORD DISTRIBUTOR POINTS MOTOR DRIVEN
HV RESISTANCE WIRE
HV RESISTANCE WIRE
DISTRIBUTOR GAP SIMULATION (0.020 GAP)
V
STANDARD SPARK FIXTURE GAP = 0.260
I
10Ω
TYPICAL CURRENT & VOLTAGE WAVE FORMS
CURRENT
VOLTAGE
P-85-436-2

Figure D-2 - Standard Ignition Test Set-Up

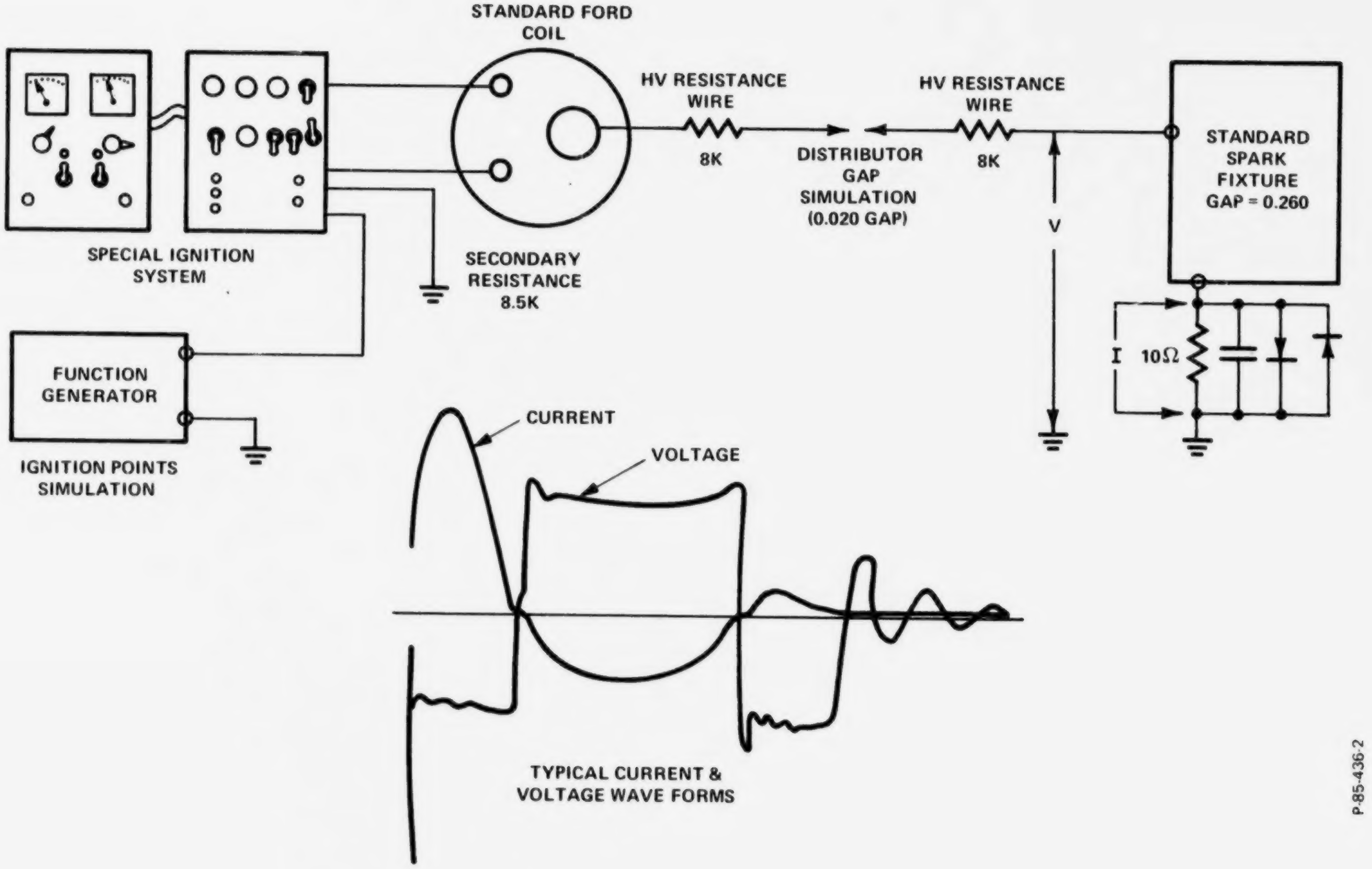
STANDARD FORD COIL
HV RESISTANCE WIRE
8K
DISTRIBUTOR GAP SIMULATION (0.020 GAP)
HV RESISTANCE WIRE
8K
STANDARD SPARK FIXTURE GAP = 0.260
V
I
10Ω
SPECIAL IGNITION SYSTEM
SECONDARY RESISTANCE 8.5K
FUNCTION GENERATOR
IGNITION POINTS SIMULATION
CURRENT
VOLTAGE
TYPICAL CURRENT & VOLTAGE WAVE FORMS
P-85-436-2

Figure D-3 - Special Ignition System Test Set-Up

TABLE TAKEN FROM "CHAMPION IGNITION AND ENGINE PERFORMANCE CONFERENCE, 1970."

		Conventional System	Capacitor Discharge System
Total Suppressor Resistance	Kilohms	25	25
Transformer Resistance	Kilohms	13	1
Input Energy	Millijoules	90	95
Energy in Spark Tail	Millijoules	19	0.9
Tail Duration	Milliseconds	2.1	0.04
Mean Tail Power	Watts	9	22
Peak Tail Power	Watts	27	43
Loss in Suppressors	Millijoules	26	86
Loss in Transformer Resistance	Millijoules	14	3.5
Loss in Distributor Gap, Assumed Equal to Plug Gap Dissipation	Millijoules	19	0.9

Dissipations Calculated From Current And Voltage Waveforms

Spark Plug Gap = 0.6 mm (0.0235 inches)

Figure D-4 - Ignition Parameters and Associated Losses

ATTACHMENT I

The waveforms of arc voltages versus time and arc current versus time contained in Figures D-5 through D-28 were taken with the test setup shown in Figures D-2 and D-3. Values of current and voltage at the same time interval were taken from the photographs. The three graphs (Figures D-29, D-30 and D-31), are examples of arc current and voltage product plotted versus time. The area under the curves represent the energy in the spark. The pertinent information about each waveform is shown in Tables D-1, D-2 and D-3.

The primary DC voltage and capacitor value could be varied on the special ignition system to change the spark intensity. These were recorded so the same spark intensity could be reproduced. The time duration would be set by observing the spark voltage on an oscilloscope. One major element cannot be reproduced on an engine and that is the arc voltage at the spark plug. Should this value change significantly from those measured in this report, then current and voltage waveforms must be taken again to determine the energy.

It should be noted that the current measurement on an engine will require a modified induction coil. The high voltage secondary must be isolated. This will allow a current sensing resistor to be installed between the engine block and the ground end of the high voltage secondary.

The waveforms shown in Figures D-32 through D-56 are presented as further examples of spark energies. These were taken with the test setup similar to Figures D-2 and D-3 except the simulated distributor gap and high voltage resistance wire was not used. The energies in these figures are higher because the loss contributing components above were omitted.

Table D-1 - Test Conditions and Test Results for Conventional Ignition

Figure	Test Conditions			Spark Test Results		
	Battery, Volts	Distributor Gap, Inch	HV Wire Resistance, K Ohms	Duration msec	Energy m joules	Intensity, Watts
D-5	13	0	8	1.93	35.5	18.0
D-6	13	0.020	8	1.50	29.3	19.5
D-7	13	0.020	16	1.35	26.5	19.6
D-8	15	0.020	16	1.50	31.5	21.0
D-9	11	0.020	16	1.05	21.1	20.0
D-10	9	0.020	16	0.86	16.5	19.2

Sensitivity - V = 1000 V/cm; I = $\frac{0.2V}{10 \text{ ohms}}$ /cm; T = 0.2 msec/cm

Table D-2 - Test Conditions and Test Results for Single SCR Mode

Figure	Test Conditions				Spark Test Results			
	Capacitance, Microfarads	Primary, Volts	Distributor Gap, Inch	HV Wire Resistance K Ohms	Duration, msec	Energy Millijoules	Intensity I, Watts	Intensity II, Watts
D-11	0.5	110	0.020	16	1.80	23.8	13.2 @ 1.8 msec	15.0 @ 93% energy
D-12	0.5	110	0.020	16	1.42	19.2	13.5 @ 1.4 msec	15.8 @ 91% energy
D-13	0.75	110	0.020	16	1.60	23.9	15.0 @ 1.60 msec	19.9 @ 94% energy
D-14	0.75	110	0.020	16	1.16	16.5	14.2 @ 1.16 msec	18.0 @ 94% energy
D-15	1.0	110	0.020	16	1.30	22.1	17.0 @ 1.30 msec	21.4 @ 95% energy
D-16	1.25	110	0.020	16	1.36	26.9	19.8 @ 1.36 msec	24.4 @ 96% energy
D-17	1.5	110	0.020	16	1.48	28.8	19.5 @ 1.48 msec	24.2 @ 96% energy
D-18	1.75	125	0.020	16	1.56	39.5	25.3 @ 1.56 msec	31.4 @ 97% energy
D-19	1.75	125	0.020	0	1.62	43.0	26.5 @ 1.62 msec	34.2 @ 95% energy
D-20	2.75	130	0.020	0	1.32	30.2	23.0 @ 1.32 msec	29.7 @ 89% energy
D-21	2.75	130	0.020	0	1.86	55.0	29.6 @ 1.86 msec	37.0 @ 96% energy
D-22	2.75	130	0	0	1.30	31.9	24.5 @ 1.30 msec	32.0 @ 95% energy
D-23	2.75	130	0.020	16	1.26	22.8	18.1 @ 1.26 msec	23.8 @ 95% energy
D-27	1.0	115	0.020	16	4.60	99.5	- -	- -
D-28	0.5	120	0.020	16	4.80	68.0	- -	- -

Sensitivity - V - 1000 V/cm; $I = \frac{0.2V}{10\ \text{ohms}}$ /cm (Figures D-11 through D-19,

$I = \frac{0.5V}{10\ \text{ohms}}$ /cm (Figures D-20 through D-23, D-27 and D-28); T = 0.2 msec/cm

Table D-3 - Test Conditions and Test Results for Double SCR Mode

Figure	Test Conditions				Spark Test Results		
	Capacitance, Microfarads	Primary, Volts	Distributor Gap, Inch	HV Wire Resistance, K Ohms	Duration, msec	Energy Millijoules	Intensity, Watts
D-24	2.75	130	0	0	1.18	46.6	39.5 @ 1.18 msec
D-25	2.75	130	0.020	0	1.31	42.3	32.3 @ 1.31 msec
D-26	2.75	130	0.020	16	1.50	40.4	26.9 @ 1.50 msec
							31.6 @ 98% energy

Sensitivity - V = 1000 V/cm; I = $\frac{0.5V}{10 \text{ ohms}}$ /cm; T = 0.2 msec/cm

FIGURES D-32 THROUGH D-35

STANDARD IGNITION, FORD COIL, 1.25 OR BALLAST R, 26 INCHES OF AUTOLITE HV WIRE (8.2K), ELECTRIC DRILL DRIVEN DISTRIBUTOR, VOLTAGE SHOWN OUT OF PHASE WITH CURRENT FOR CLARITY

I = 0.2 V/CM (10)
V = 1000V/CM
TIME = 0.5 M SEC/CM

D-32 BATTERY V = 9V

D-33 BATTERY V = 11V

D-34 BATTERY V = 13V

D-35 BATTERY V = 15V

ALL WAVEFORMS, FIGURES D-36 THROUGH D-47, ARE WITH SPECIAL IGNITION SYSTEM DOUBLE SCR MODE
I = 0.2V/CM (10Ω)
V = 1000V/CM

D-36 0.25 ufd CAP: PRIMARY V = 120V: TIME = 0.2 M SEC/CM
D-37 0.25 ufd CAP: PRIMARY V = 120V: TIME = 0.1 M SEC/CM
D-38 0.5 ufd CAP: PRIMARY V = 114V: TIME = 0.2 M SEC/CM
D-39 0.5 ufd CAP: PRIMARY V = 114V: TIME = 0.1 M SEC/CM
D-40 1.0 ufd CAP: PRIMARY V = 105V: TIME = 0.2 M SEC/CM
D-41 1.0 ufd CAP: PRIMARY V = 105V: TIME = 0.1 M SEC/CM
D-42 1.25 ufd CAP: PRIMARY V = 102V: TIME = 0.2 M SEC/CM
D-43 1.25 ufd CAP: PRIMARY V = 102V: TIME = 0.1 M SEC/CM
D-44 0.5 ufd CAP: PRIMARY V = 105V: TIME = 0.2 M SEC/CM
D-45 1.5 ufd CAP: PRIMARY V = 105V: TIME = 0.1 M SEC/CM
D-46 1.75 ufd CAP: PRIMARY V = 104V: TIME = 0.2 M SEC/CM
D-47 1.75 ufd CAP: PRIMARY V = 104V: TIME = 0.1 M SEC/CM

ALL WAVEFORMS FIGURES D-48 THROUGH D-58 SINGLE MODE SCR; I = 0.2V/CM (10Ω); V = 1000V/CM

D-48 0.5 ufd CAP: PRIMARY V = 100V: TIME = 0.2 M SEC/CM
D-49 0.5 ufd CAP: PRIMARY V = 100V: TIME = 0.1 M SEC/CM
D-50 1.0 ufd CAP: PRIMARY V = 100V: TIME = 0.2 M SEC/CM
D-51 1.0 ufd CAP: PRIMARY V = 100V: TIME = 0.1 M SEC/CM
D-52 1.5 ufd CAP: PRIMARY V = 100V: TIME = 0.2 M SEC/CM
D-53 1.5 ufd CAP: PRIMARY V = 100V: TIME = 0.1 M SEC/CM
D-54 0.25 ufd CAP: PRIMARY V = 120V: TIME = 0.2 M SEC/CM
D-55 0.25 ufd CAP: PRIMARY V = 120V: TIME = 0.1 M SEC/CM
D-56 0.25 ufd CAP PRIMARY V = 120V: TIME = 0.05 M SEC/CM

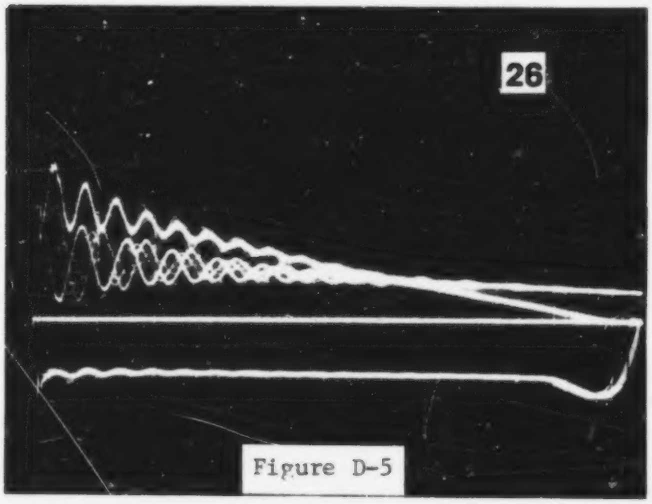

Figure D-5

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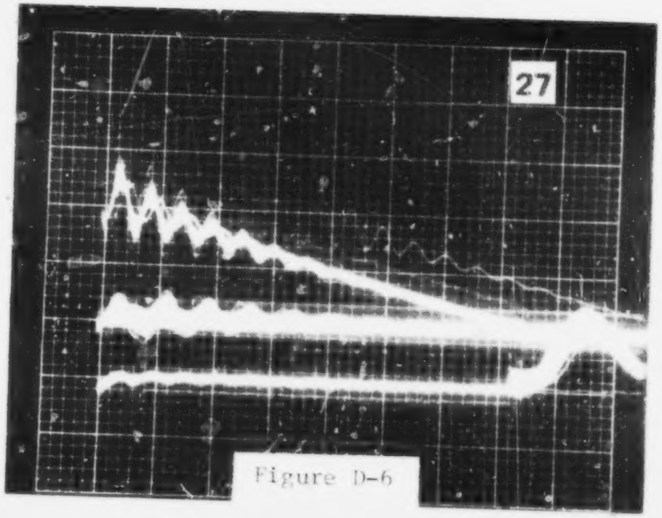

Figure D-6

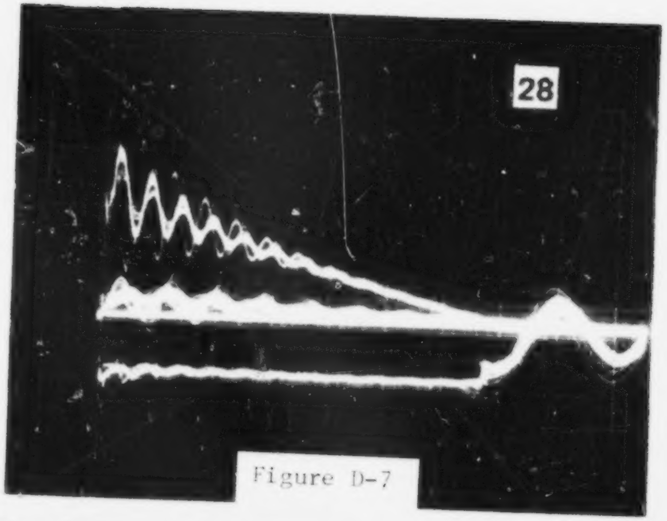

Figure D-7

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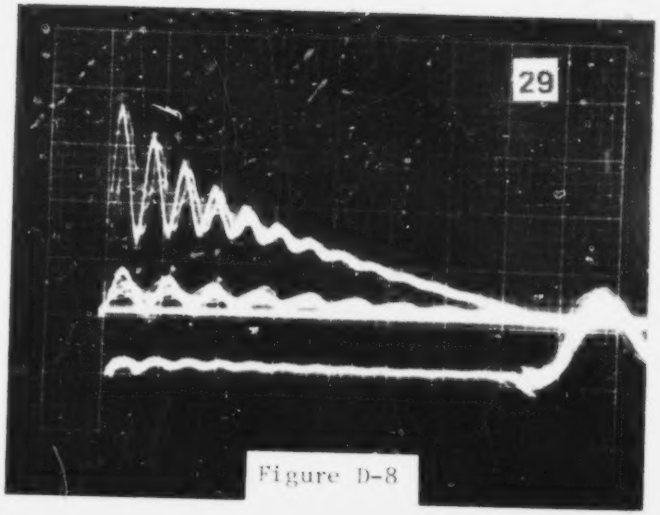


Figure D-8

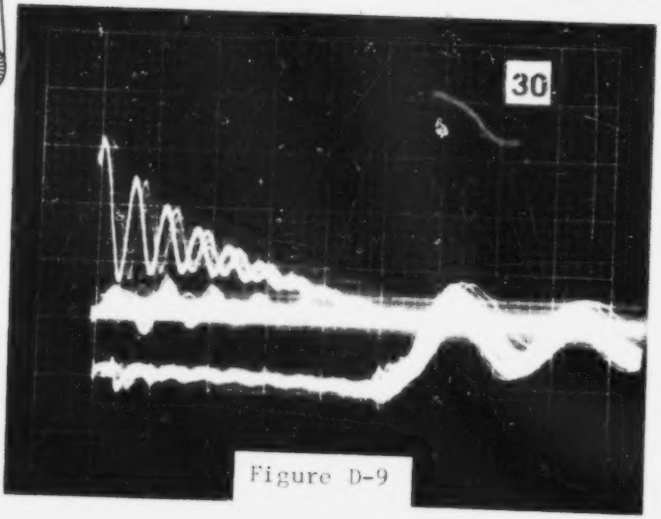


Figure D-9

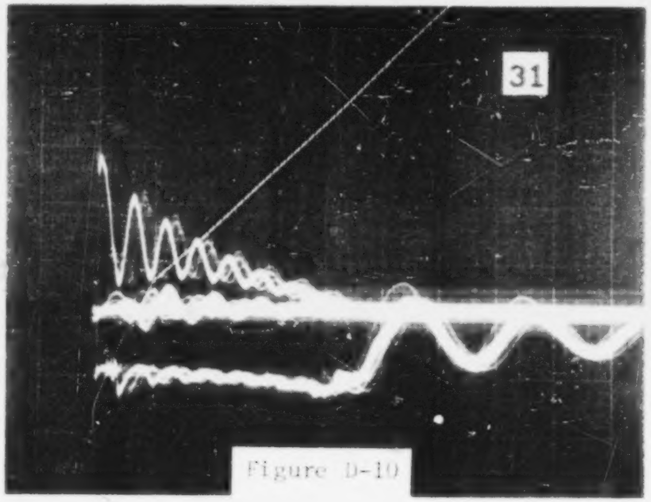


Figure D-10

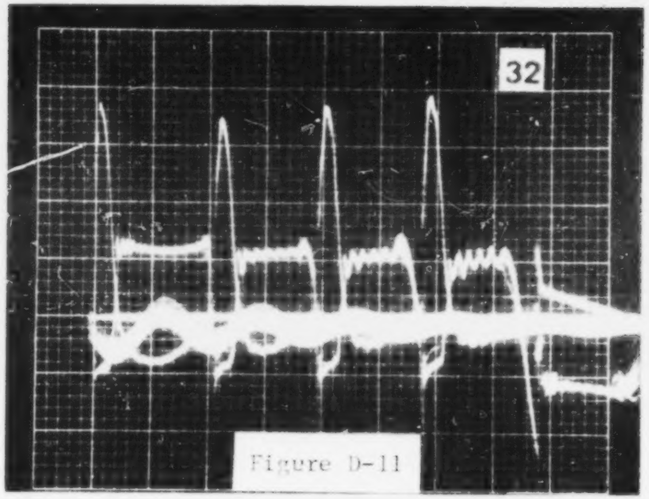


Figure D-11

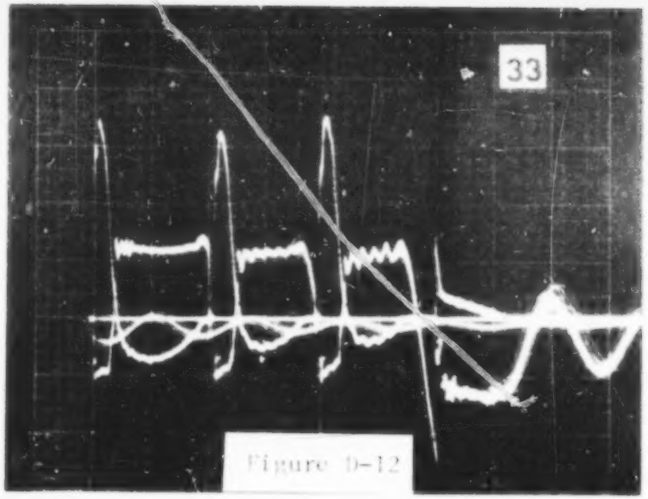


Figure D-12

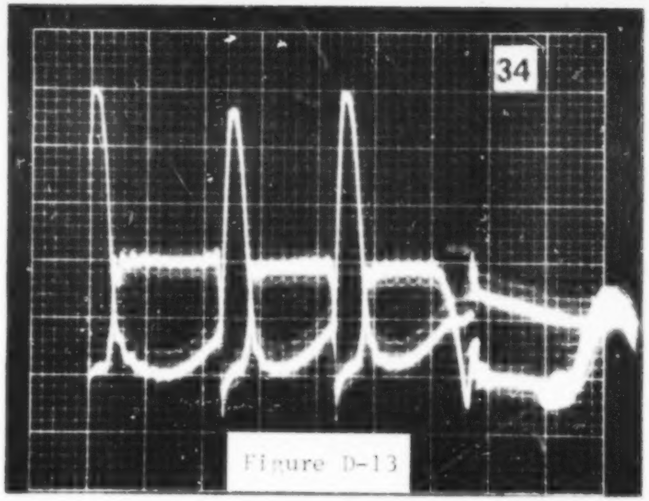
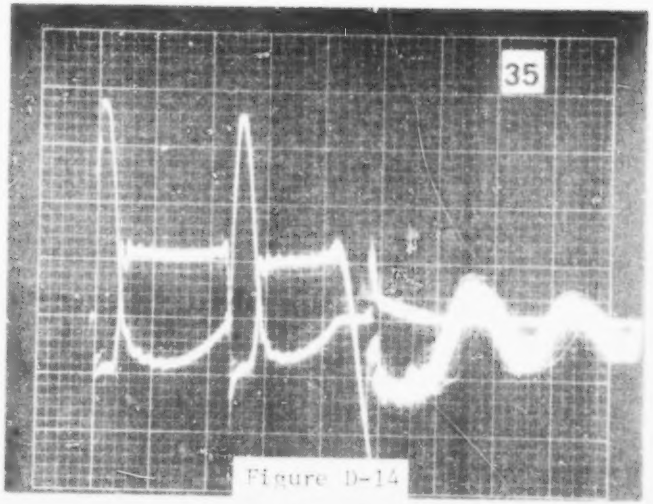


Figure D-13



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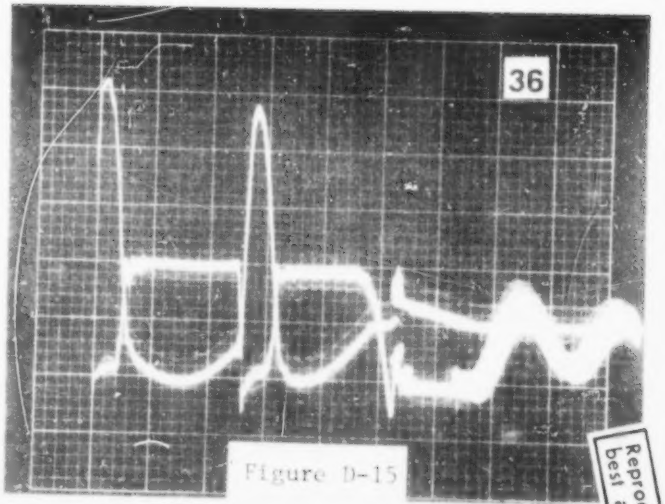

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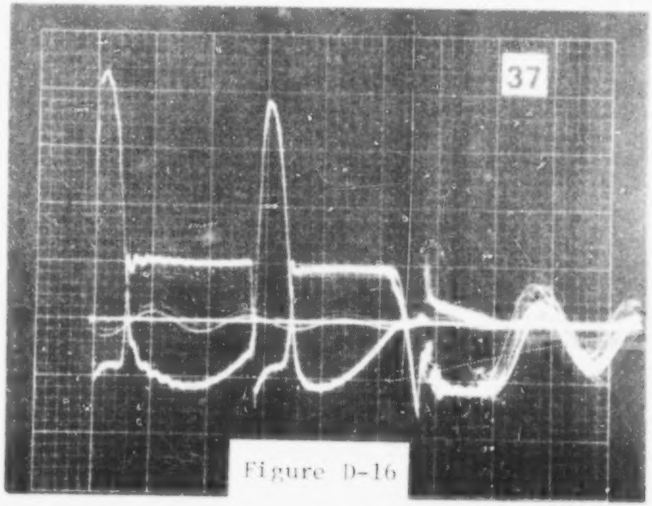

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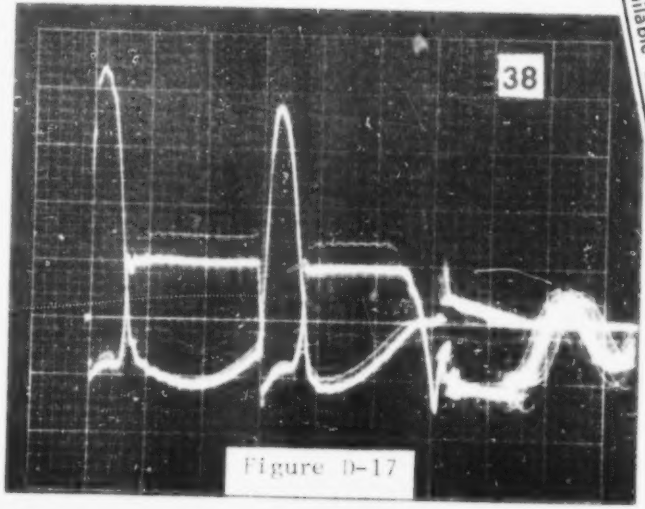

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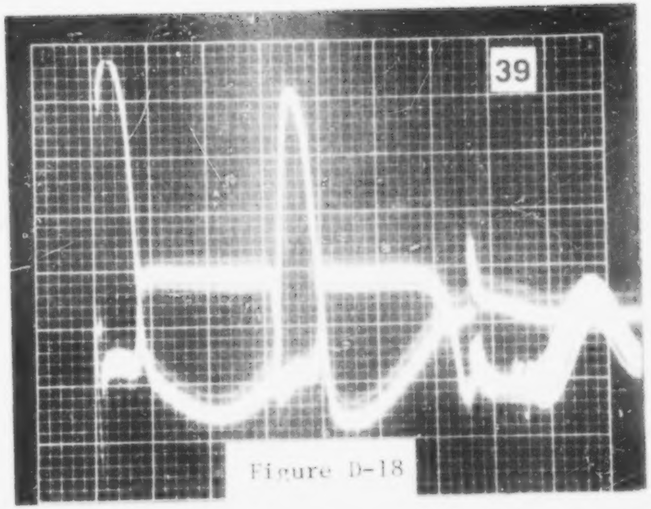

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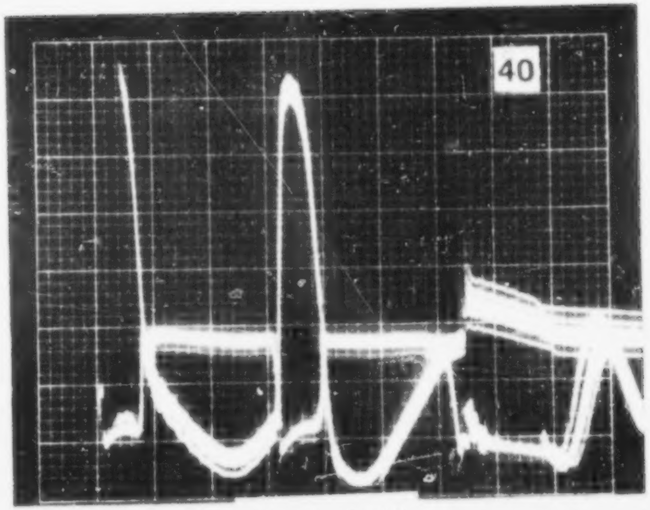

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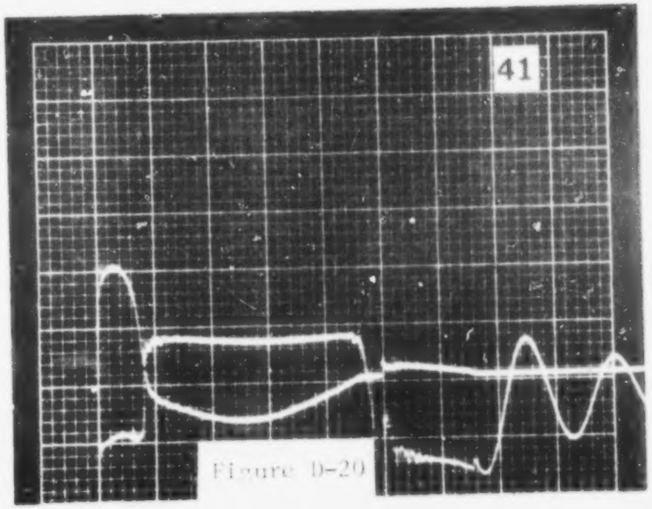

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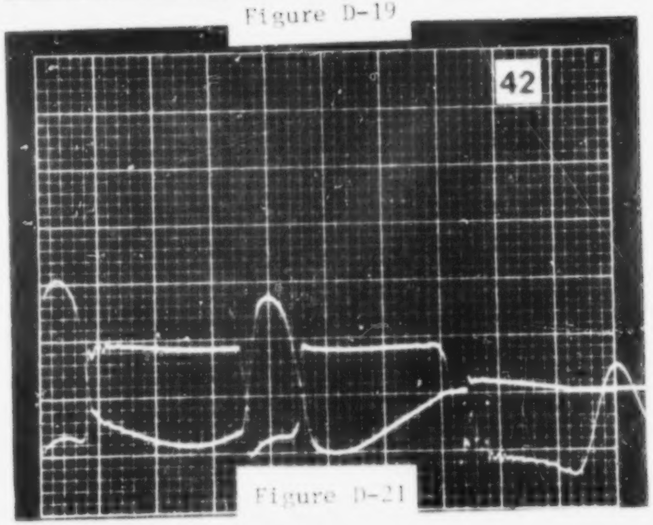

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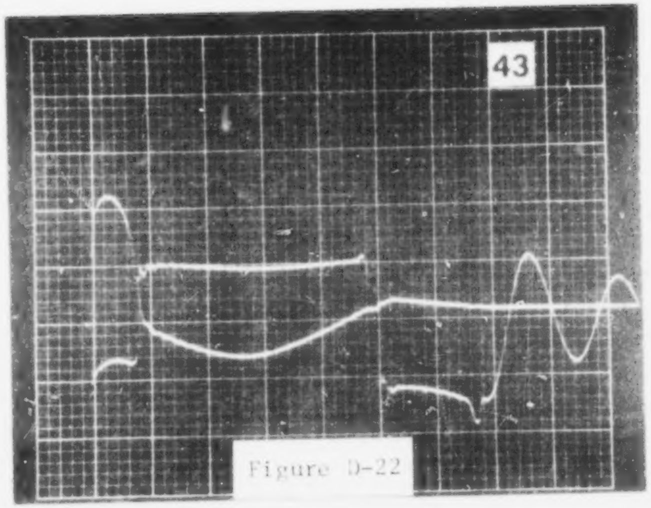

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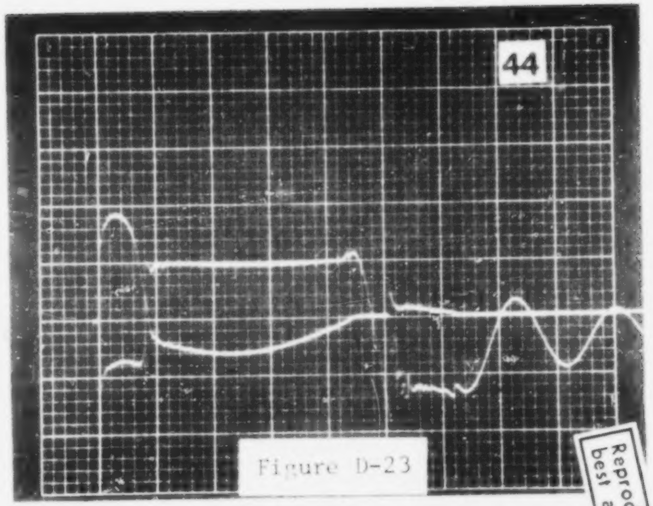

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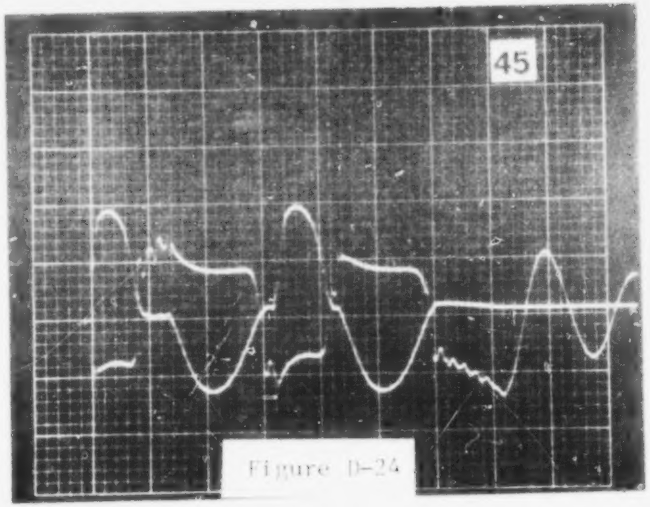

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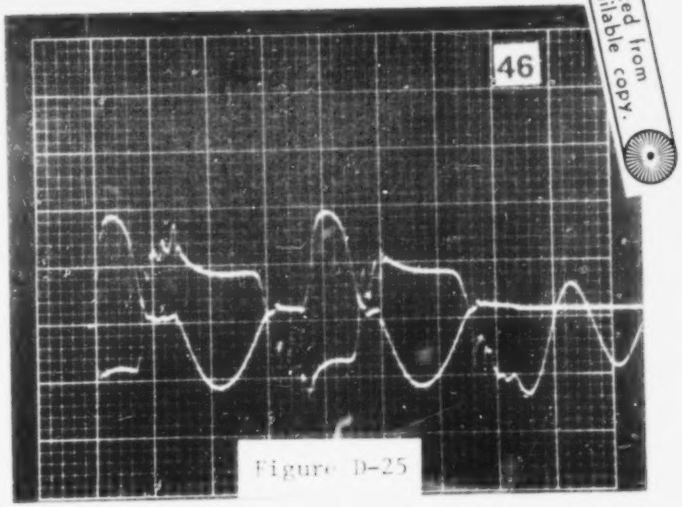

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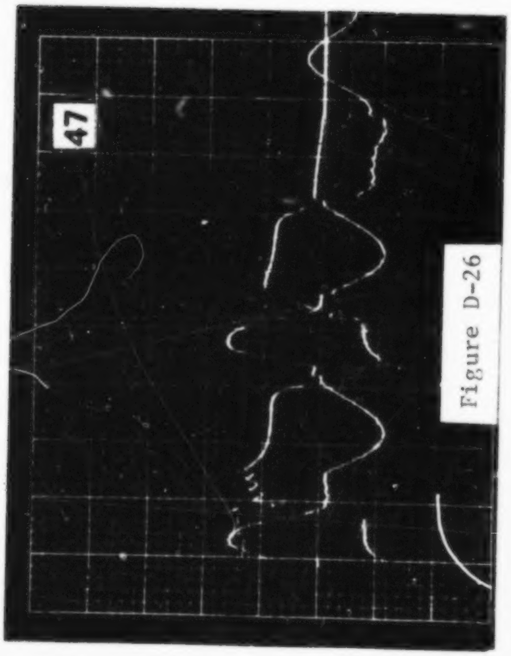

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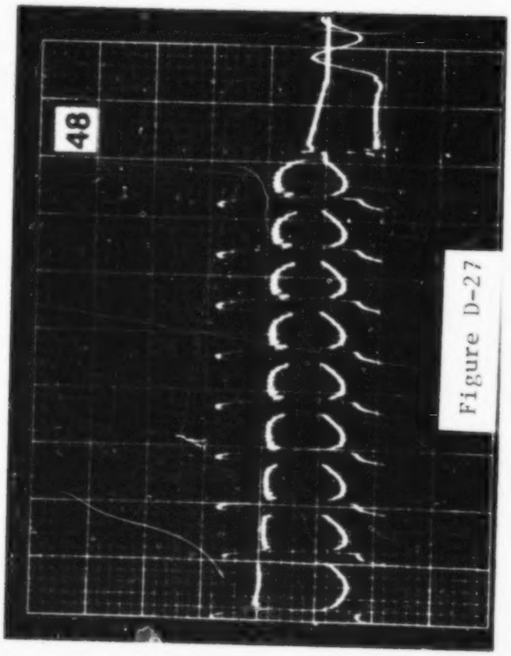

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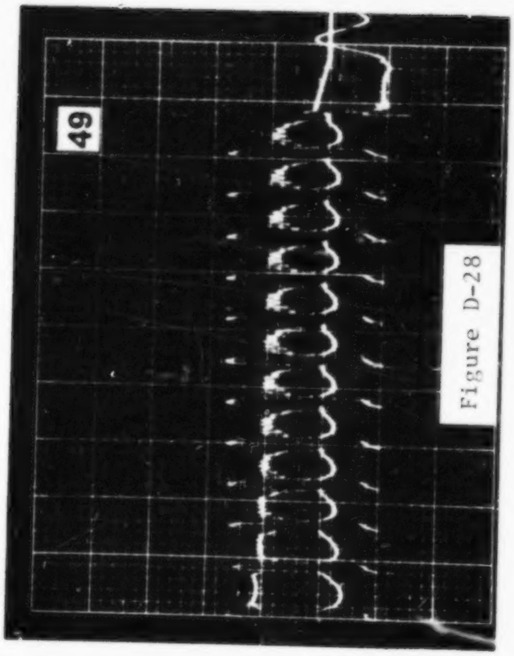

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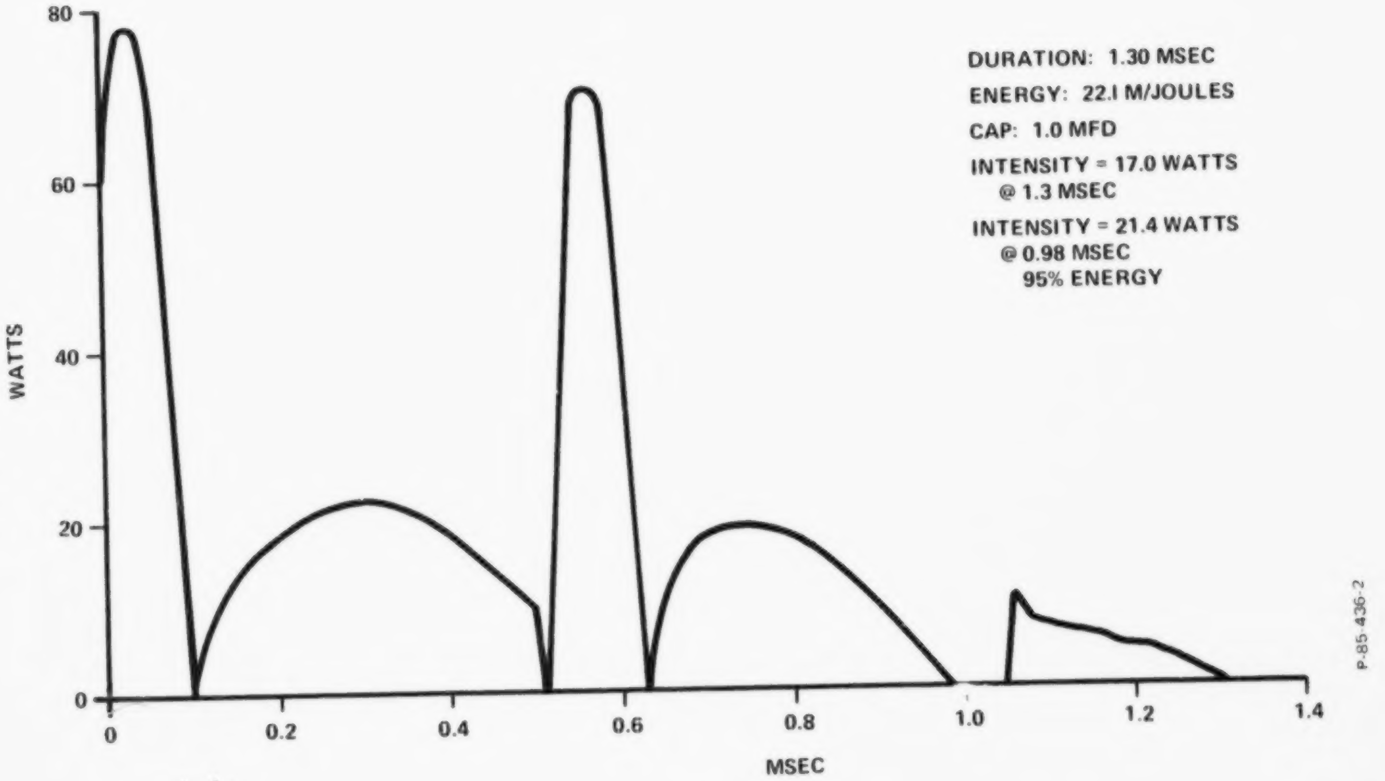


Figure D-29 – Single SCR Mode Distributor Gap and 16K HV Resistance Wire

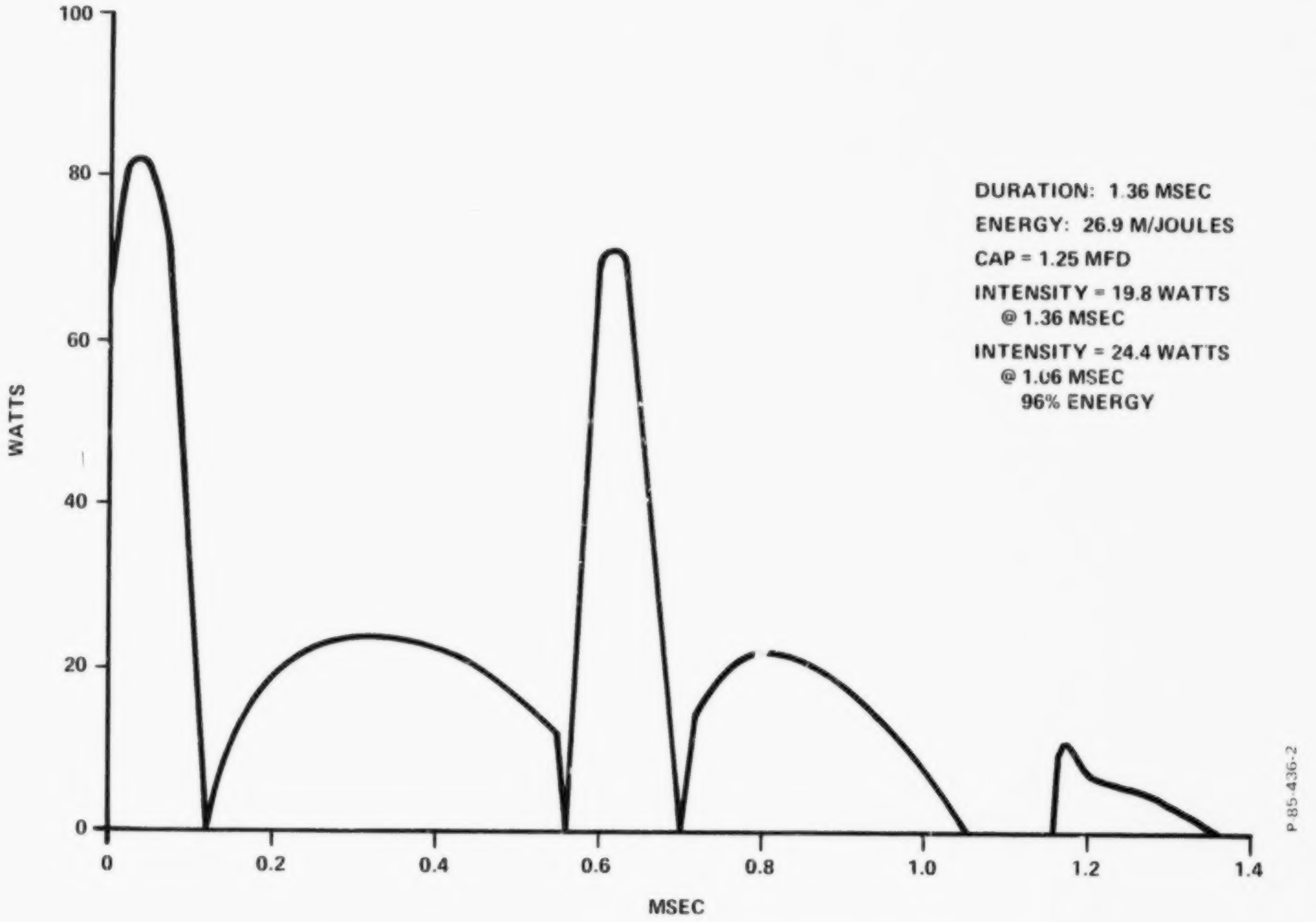


Figure D-30 - Single SCR Mode Distributor Gap and 16K HV Resistance Wire

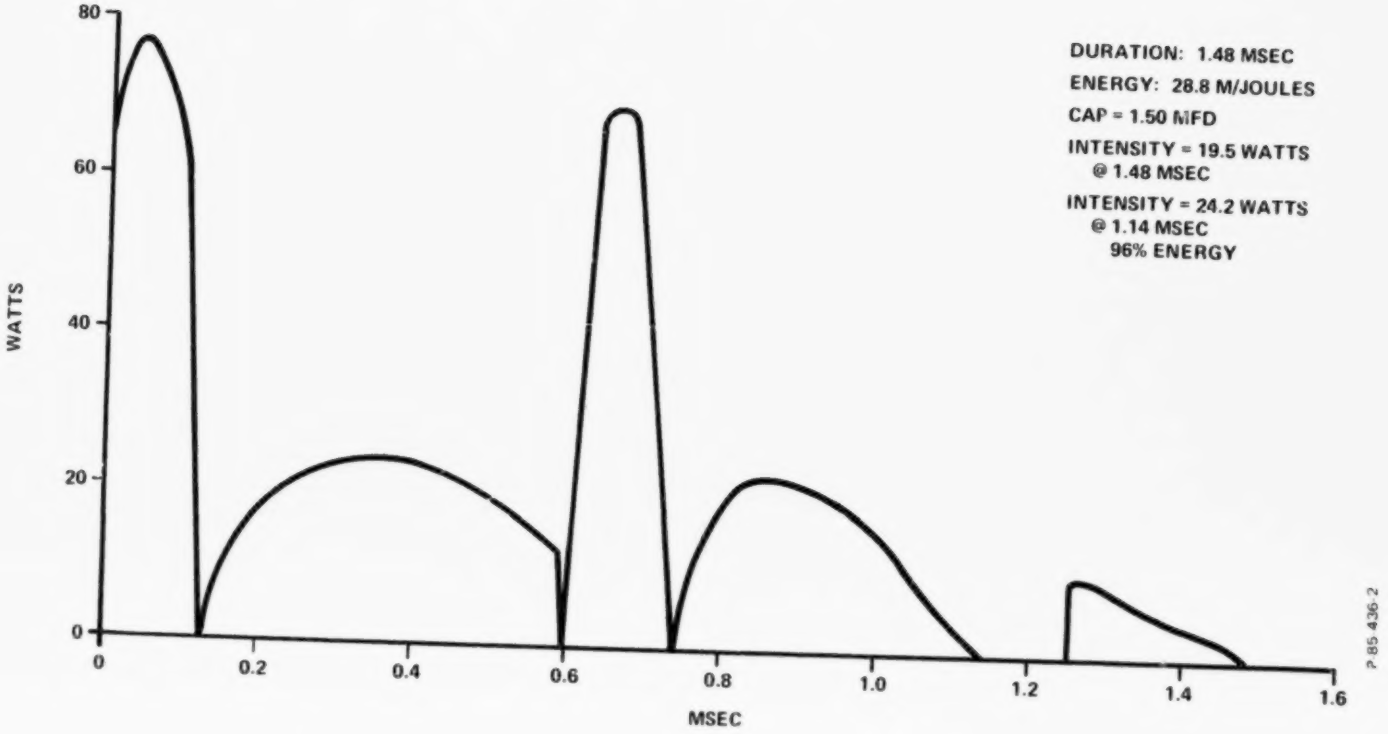
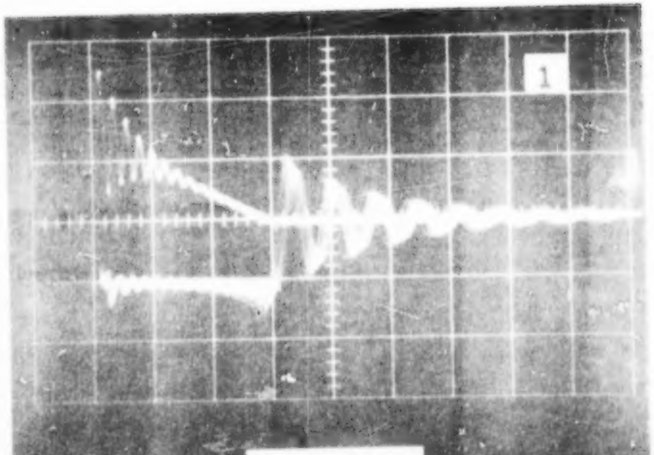


Figure D-31 - Single SCR Mode Distributor Gap and 16K HV Resistance Wire



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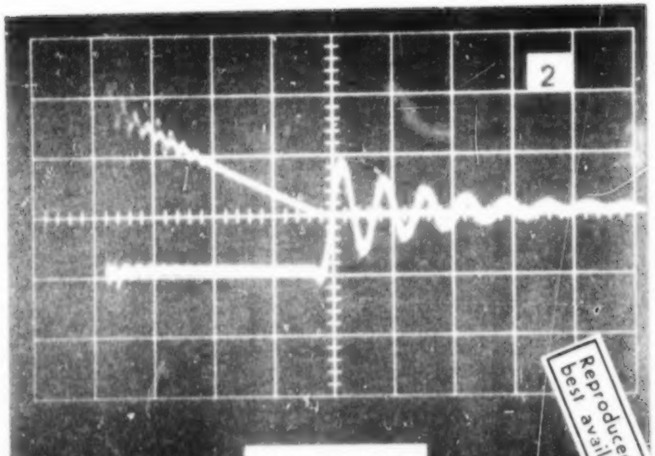

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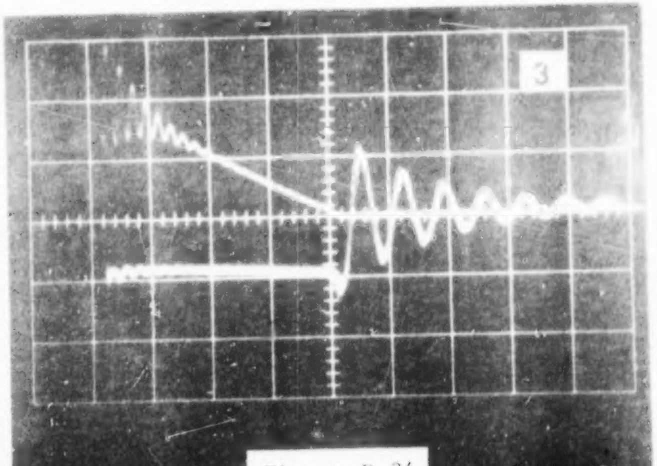

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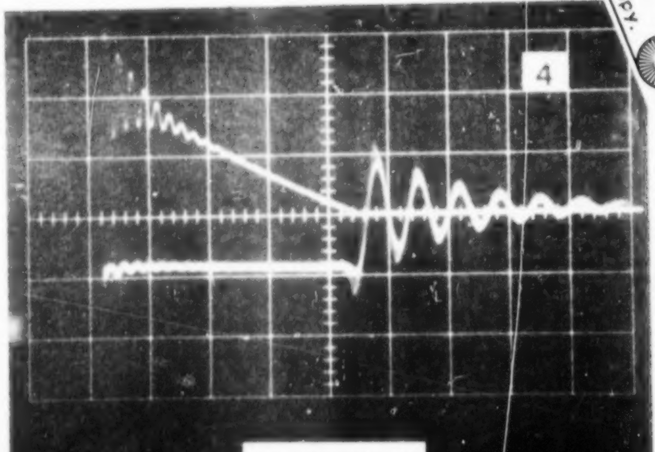

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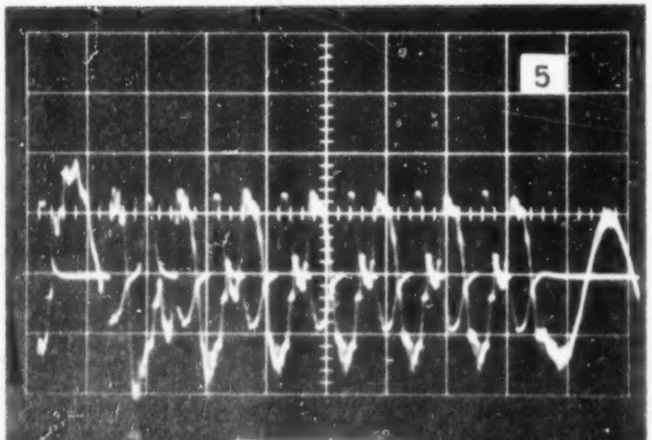

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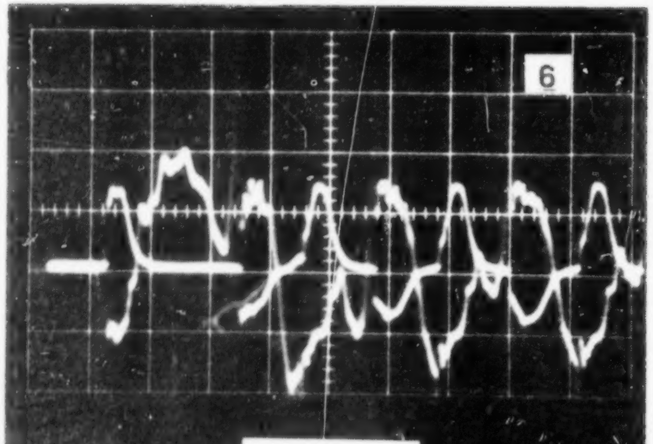

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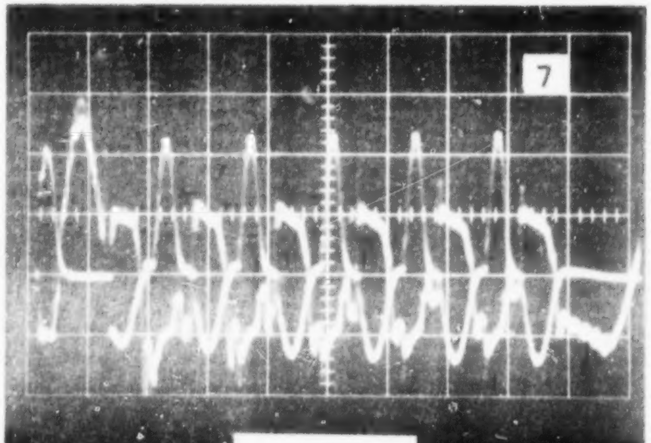

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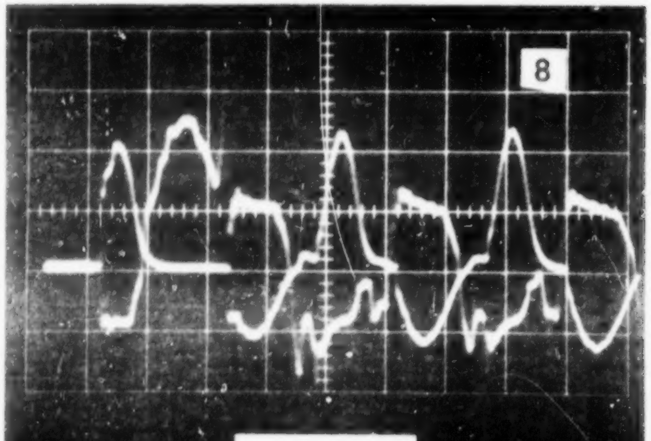

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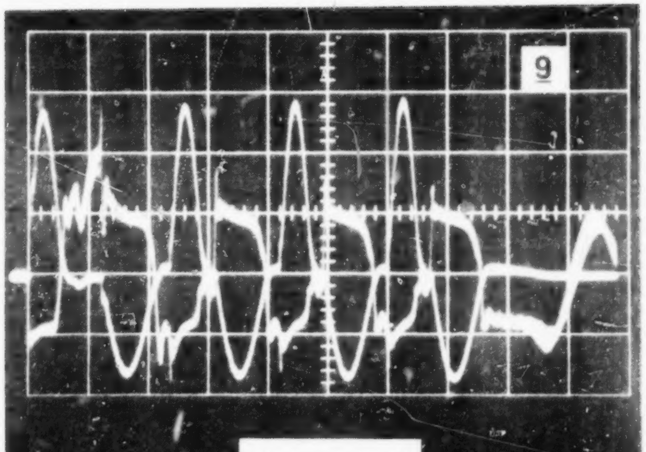

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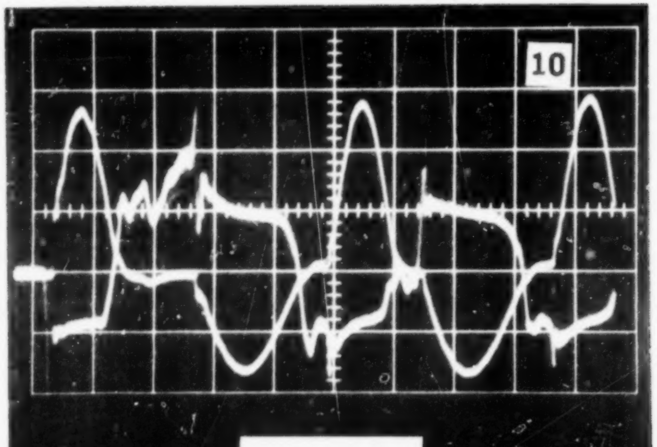

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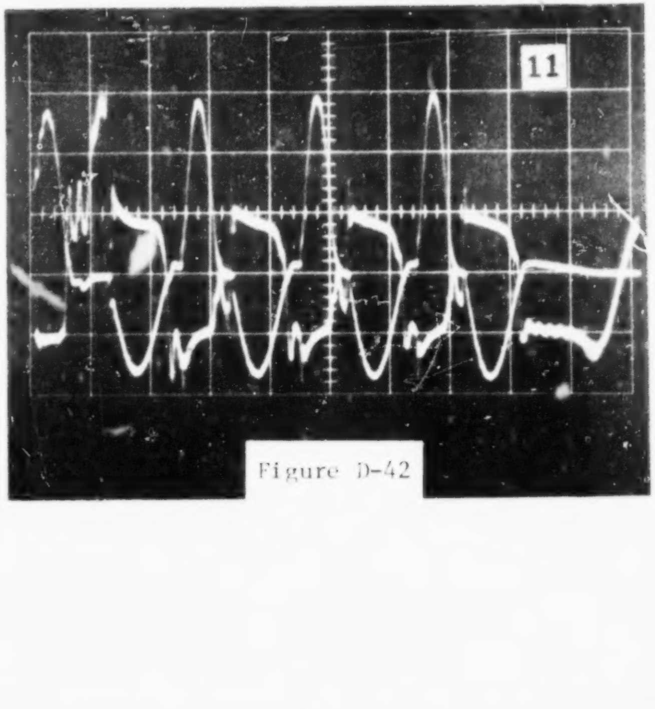

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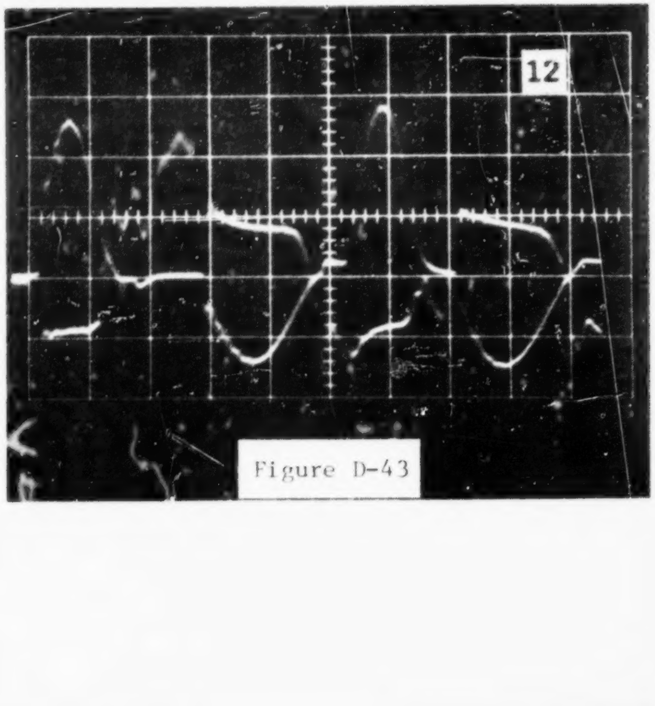

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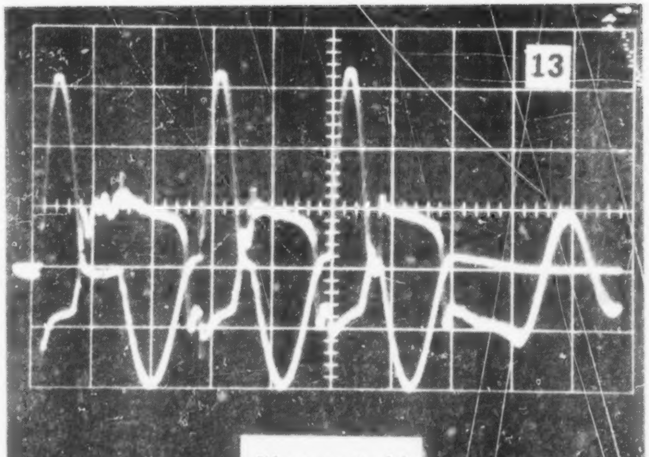

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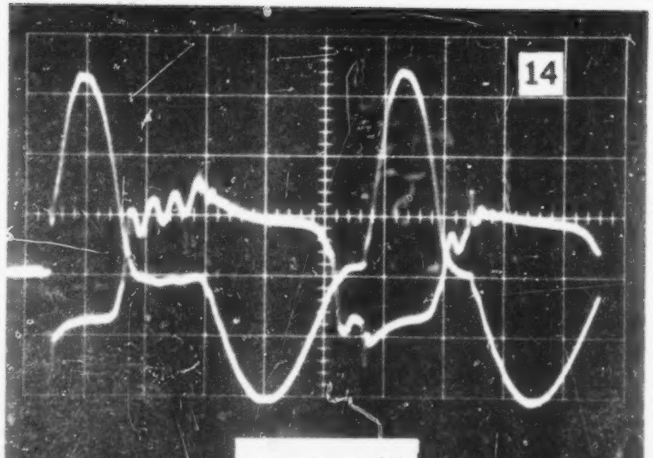

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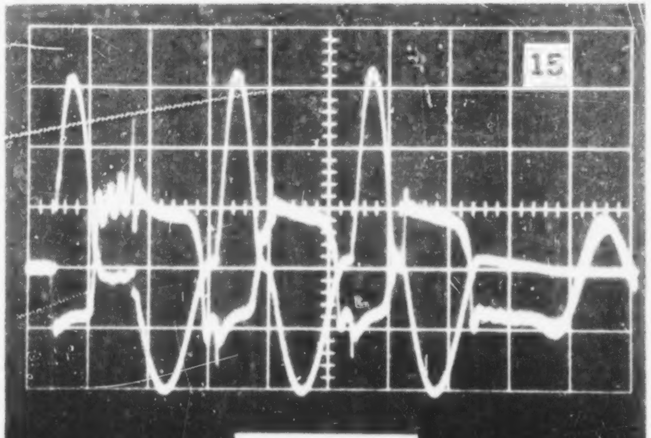

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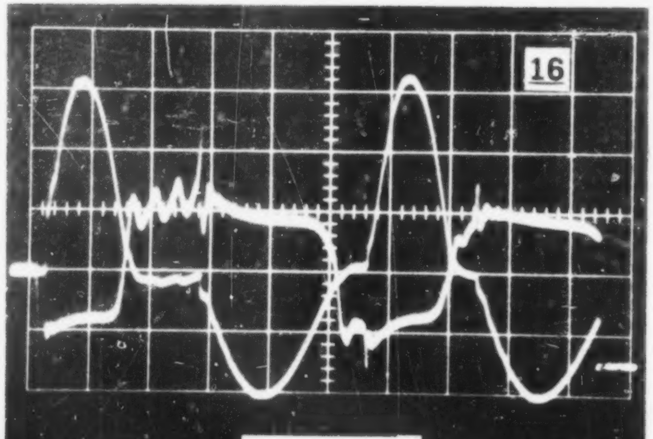

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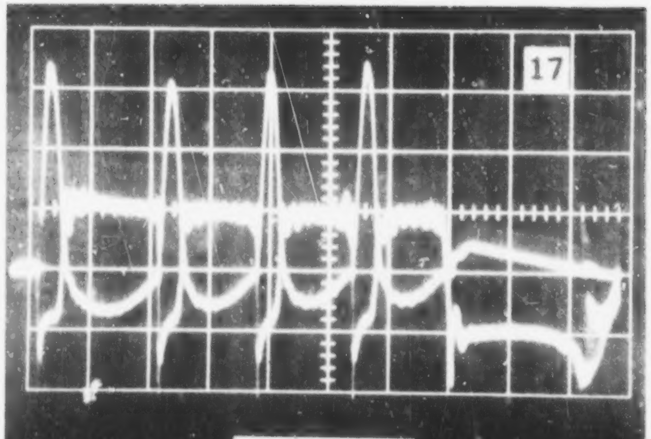

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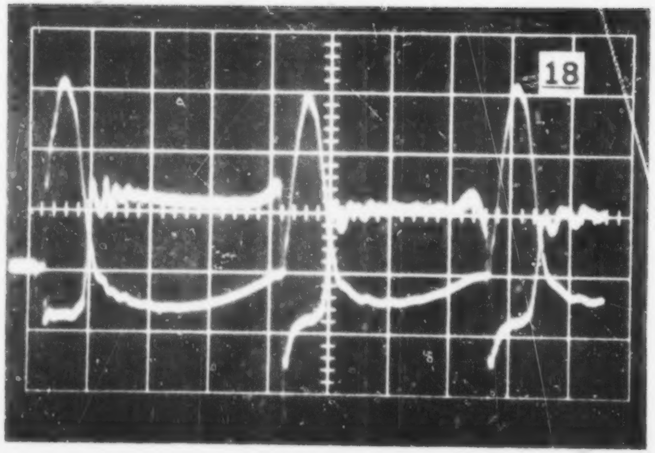

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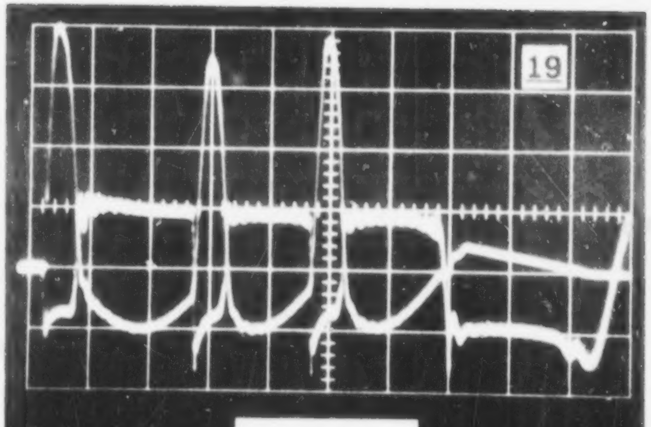
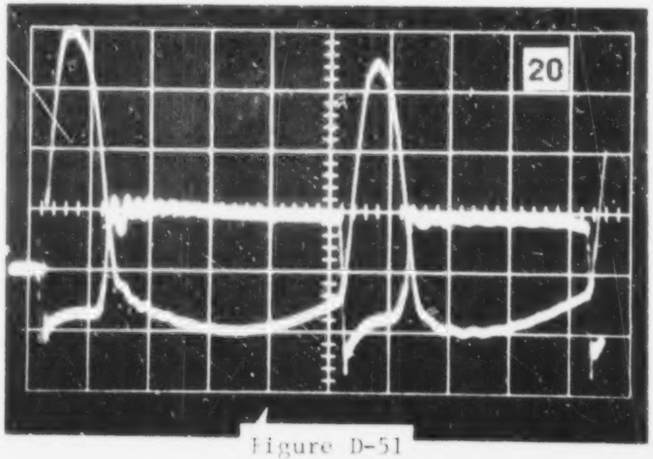


Figure D-50



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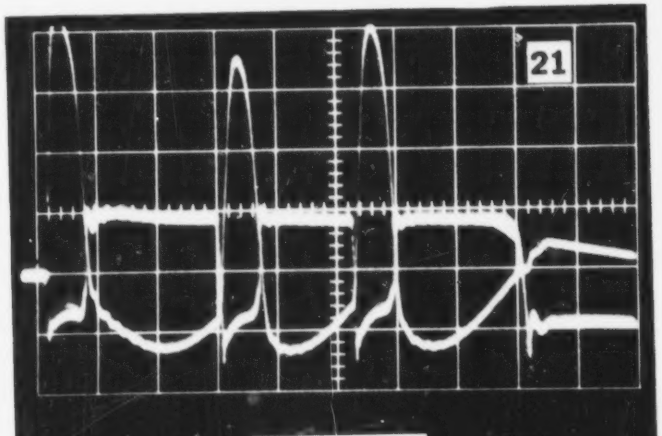

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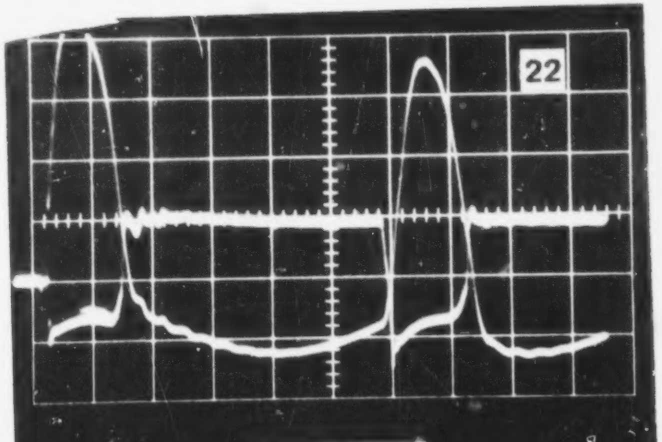

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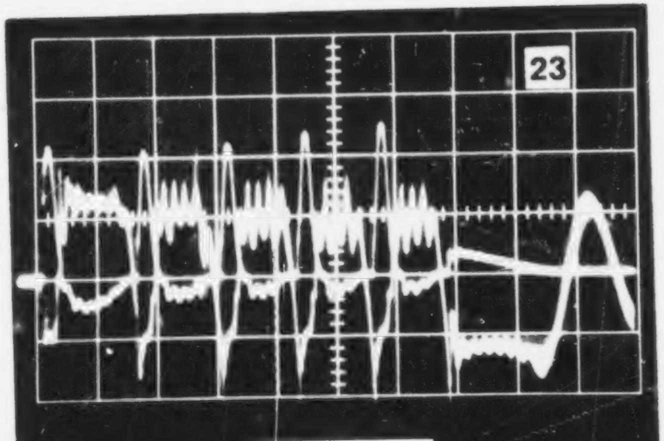

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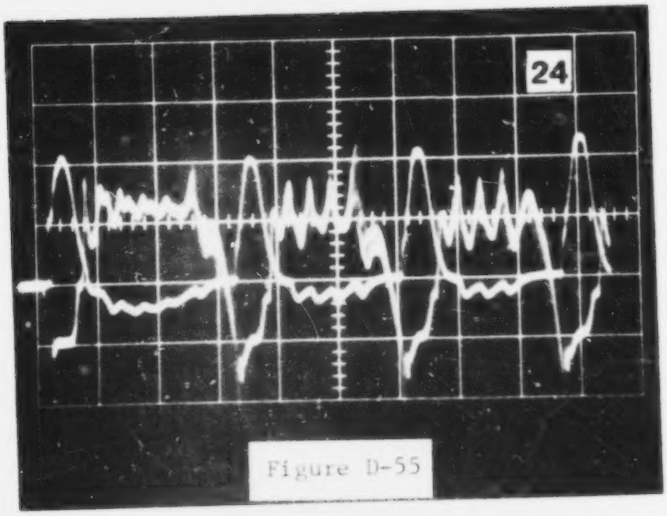

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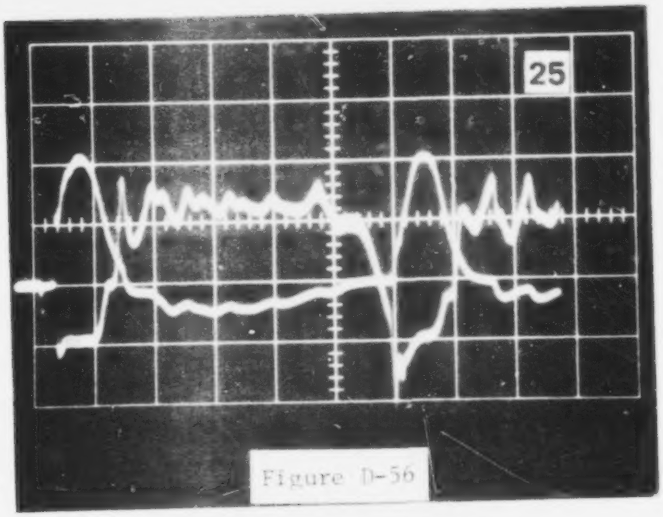

Figure D-56

APPENDIX E

INLET VALVE THROTTLING CAMSHAFT LOBE ANALYSIS

The inlet valve throttling task of this project required that three standard Ford 429 engine camshafts have the inlet valve lobes reground to lower lifts to correspond to approximately 100, 400, and 800 lb/hr equivalent throttle position air flow. It was assumed that the inlet valve timing and the opening and closing ramps would not be altered. The following analysis, to predict the inlet valve lobe lift, was based on data gathered from the idle run No. 12, November 30, 1970, of the Bendix engine matrix study and selected power points. The appropriate data and schematic of a standard induction system are shown in Figure E-1. It was further assumed that the low engine speed reduces the dynamic or inertial effects of the gas flow in the induction system.

The orifice coefficient for the intake valve was assumed to be 0.80 where normal throttling takes place and valve lift is relatively large. For intake valve throttling, since the lift was expected to be considerably less than normal, a coefficient of 0.65 was used. It was further assumed that the low engine speed reduces the dynamic or inertial effects of the gas flow in the induction system.

Referring to Figure E-1, the average total mass flow rate into the engine (W_1) is 0.0297 lbs/sec. Thus, the average cylinder mass flow rate (W_3) is 0.00371 lbs/sec. The total mass of air inducted into a cylinder per cycle can be determined from a multiplication of the average flow rate (W_3) by the elapsed time per cycle (t). However, the intake valve is only open a portion of the cycle time from a crank position of 16° BTC to 60° ABC. Integrating the lift lobe profile over one revolution of the camshaft (one engine cycle) indicated that the intake valve is effectively fully opened (lift $X = 0.441$ inches) for a time (t_o) equivalent to 21.2 percent of the cycle time. Taking this into consideration, the instantaneous flow rate (W_v) through the fully opened valve can be found from:

$$W_v = \frac{W_3}{0.212}$$

$$= \frac{0.00371}{0.212} \qquad (1)$$

$$= 0.0175 \text{ lbs/sec}$$

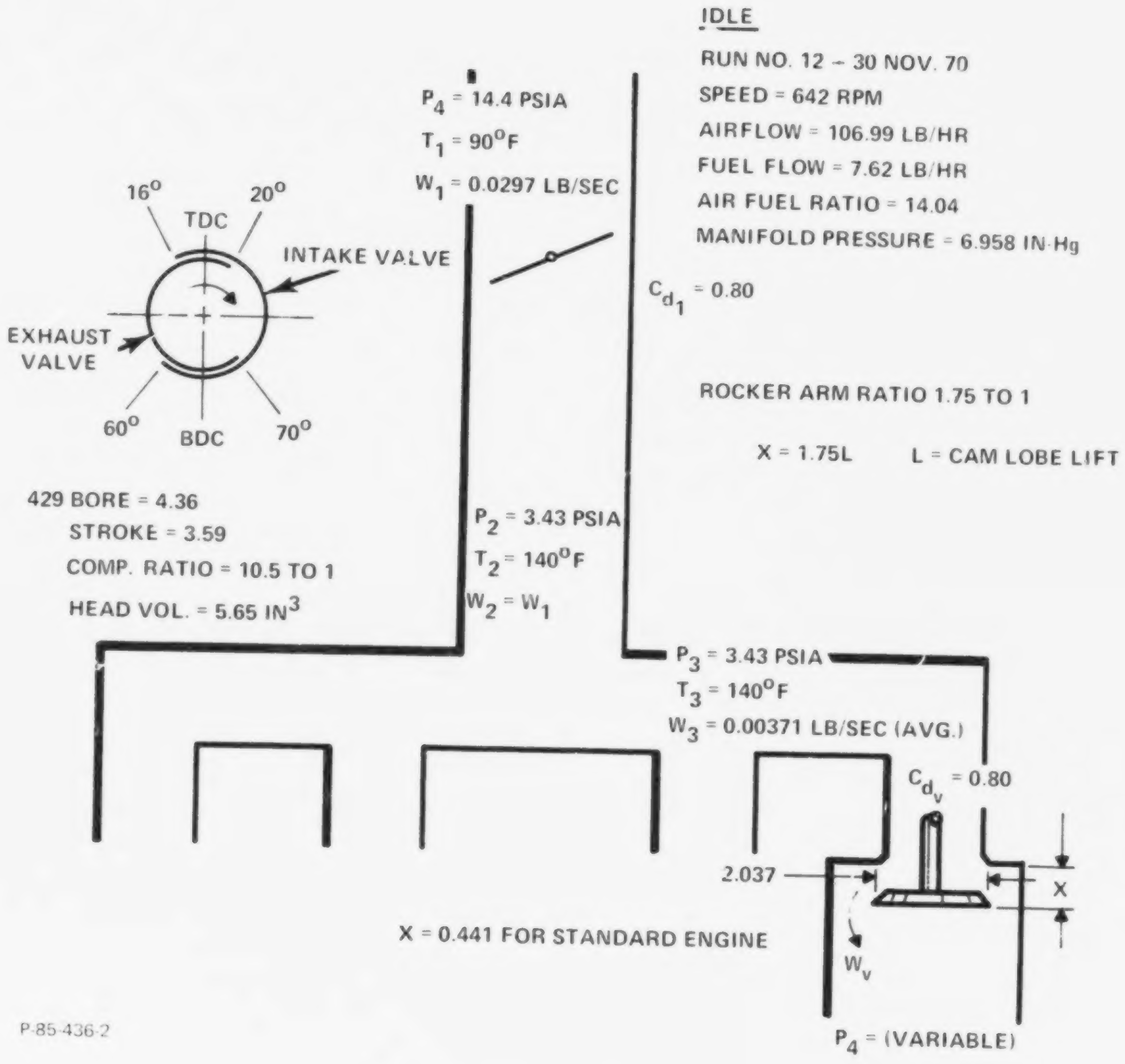
IDLE
RUN NO. 12 – 30 NOV. 70
SPEED = 642 RPM
AIRFLOW = 106.99 LB/HR
FUEL FLOW = 7.62 LB/HR
AIR FUEL RATIO = 14.04
MANIFOLD PRESSURE = 6.958 IN-Hg
P_4 = 14.4 PSIA
T_1 = 90°F
W_1 = 0.0297 LB/SEC
16°
20°
TDC
INTAKE VALVE
EXHAUST VALVE
60°
BDC
70°
C_{d_1} = 0.80
ROCKER ARM RATIO 1.75 TO 1
X = 1.75L
L = CAM LOBE LIFT
429 BORE = 4.36
STROKE = 3.59
COMP. RATIO = 10.5 TO 1
HEAD VOL. = 5.65 IN^3
P_2 = 3.43 PSIA
T_2 = 140°F
W_2 = W_1
P_3 = 3.43 PSIA
T_3 = 140°F
W_3 = 0.00371 LB/SEC (AVG.)
C_{d_v} = 0.80
2.037
X
X = 0.441 FOR STANDARD ENGINE
W_v
P_4 = (VARIABLE)
P-85-436-2

Figure E-1 - Induction System and Data

The pressure downstream from the intake valve (P_4) is less than the intake manifold pressure (P_3) and can be found from the following thermodynamic equation for mass flow rate for gases:

$$W_v = C_d A_o \frac{P_u}{\sqrt{T_u}} C_2 \; f_1 \; (P_d/P_u) \qquad (2)$$

where

C_d = orifice discharge coefficient

A_o = physical area of orifice, in^2

P_u = upstream stagnation pressure, psia

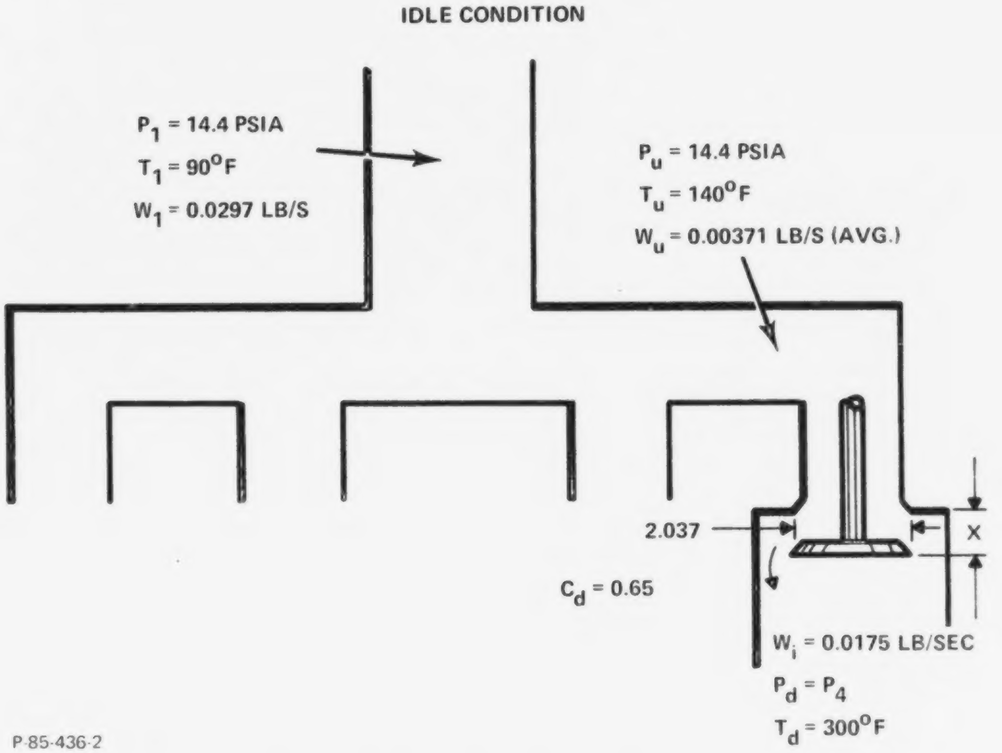
IDLE CONDITION
P1 = 14.4 PSIA
T1 = 90°F
W1 = 0.0297 LB/S
Pu = 14.4 PSIA
Tu = 140°F
Wu = 0.00371 LB/S (AVG.)
2.037
X
Cd = 0.65
Wi = 0.0175 LB/SEC
Pd = P4
Td = 300°F
P-85-436-2

Figure E-2 - Inlet Valve Throttling Schematic

P_d = downstream stagnation pressure, psia

T_u = upstream stagnation absolute temperature, °R

C_2 = gas property thermodynamic constant; for air 0.532 (degrees R)$^{1/2}$/sec.

$f_1(P_d/P_u)$ = obtained from tabulated values for various gases

$$= \frac{(P_d/P_u)^{1/k}\sqrt{1 - (P_d/P_u)^{k-1/k}}}{(P_d/P_u)^{1/k}_{\text{Critical}}\ \sqrt{1 - (P_d/P_u)^{k-1/k}_{\text{Critical}}}}$$

k = ratio of the gas specific heat values

$$(P_d/P_u)\ \text{Critical} = \left(\frac{2}{k+1}\right)^{k/k-1}$$

The area (A_o) is determined from:

$$A_o = \pi\ D_v\ X \qquad (3)$$

where

D_v = intake valve metering diameter, in.

X = valve total lift, in.

Substitution of the known quantities into equation (2) where $P_3 = P_u$ and $P_4 = P_d$ gives:

$$0.0175 = \frac{0.80\ (2.037)\ \pi\ (0.441)\ 3.43\ (0.532)}{\sqrt{600}}\ f_1\left(\frac{P_4}{3.43}\right)$$

$$0.10402 = f_1\left(\frac{P_4}{3.43}\right)$$

From a table of values for the f_1 function = 0.10402,

$$P_4/P_3 = 0.9977$$

and

$$P_4 = 0.9977\ (3.43)$$

$$= 3.42 \text{ psia}$$

Referring now to Figure E-2 for an intake valve throttled engine, it can be seen that the upstream pressure is 14.4 psia instead of 3.43 psia as was the case for the normally throttled engine. Therefore, the new valve lift (X) can be found using the form of equation (2):

$$0.0175 = \frac{0.65\ (2.037)\ \pi\ (x)\ 14.4\ (0.532)}{\sqrt{760}} \quad (1)$$

$$x = 0.01513 \text{ inch}$$

Note that the value for $f_1(P_d/P_u)$ in this case is (1) because the pressure ratio is higher than the critical value and flow through the intake valve is sonic.

The rocker arm ratio (β) for this engine is 1.75 to 1; therefore, the camshaft lobe lift (ℓ) is found from:

$$\ell = \frac{X}{\beta}$$

$$\ell = \frac{0.0151}{1.75} \qquad (4)$$

$$= 0.008645 \text{ inch}$$

In order to design the new lobe shape it was necessary to know the existing shape of the lobe. In addition, the opening ramp, closing ramp and maximum geometric acceleration of the standard intake lobe should be maintained. The new reground lobe geometric acceleration should not exceed that of the standard camshaft if the same valve train mechanism is retained. Data on the intake lobe lift versus position was obtained from the Ford Motor Company.

The idle grind profile was generated by fairing smooth curves into the opening and closing ramp profiles and made tangent to the desired 0.00865 lift. The ordinates of the curve were then recorded and the resulting velocities and accelerations computed. The resulting accelerations are less than the standard Ford cam profile and the idle grind lift profile generated is considered acceptable.

The power points selected for the off-idle condition and WOT correspond to air flows of 400 lbs/hr and 800 lbs/hr and manifold pressures of 10.5 and 11.25 psia, respectively.

Using the same analytical technique as for the idle grind, the average flow rate across the intake valve for the 400 lbs/hr power point was found to be:

$$W_4 = \frac{400}{3600\ (0.212)\ 8}$$

$$= 0.06551 \text{ lbs/sec}$$

The average cylinder pressure during the intake stroke was found from:

$$0.06551 = \frac{0.80\ (2.037)\ (0.441)\ 10.5\ (0.532)}{\sqrt{600}}\ f_1 \left(\frac{P_4}{10.5}\right)$$

$$0.12619 = f_1 \left(\frac{P_4}{10.5}\right)$$

Therefore, the flow is not critical across the standard inlet port and the average cylinder pressure is:

$$P_4 = 10.46 \text{ psia}$$

Table E-1 - Lift lobe Data for Regrind of Ford Camshaft* Idle Grind

Degrees From ℄	Opening Lift	Closing Lift
0	.00865	.00865
1	▲	▲
2	|	|
3	|	|
4	|	|
5	|	|
6	|	|
7	|	|
8	|	|
9	|	|
10	|	|
11	|	|
12	|	|
13	|	|
14	|	|
15	|	|
16	|	|
17	|	|
18	|	|
19	|	|
20	|	|
21	|	|
22	|	|
23	|	|
24	|	|
25	|	|
26	|	|
27	|	|
28	▼	▼

Degrees From ℄	Opening Lift	Closing Lift
29	▲	▲
30	|	|
31	|	|
32	|	|
33	|	|
34	|	|
35	|	|
36	|	|
37	|	|
38	|	|
39	|	|
40	|	|
41	|	|
42	|	|
43	|	|
44	|	|
45	|	|
46	|	|
47	|	|
48	|	|
49	|	|
50	|	|
51	|	|
52	|	▼
53	|	.00865
54	▼	.00859
55	.00865	.00847
56	.00864	.00829
57	.00828	.00806

Degrees From ℄	Opening Lift	Closing Lift
58	.00788	.00780
59	.00733	.00752
60	.00655	.00722
61	.00581	.00691
62	.00499	.00660
63	.00417	.00630
64	.00344	.00600
65	.00287	.00570
66	.00241	.00540
67	.00200	.00510
68	.00160	.00480
69	.00120	.00450
70	.00080	.00420
71	.00045	.00390
72	.00020	.00360
73	.00005	.00330
74	0	.00305
75		.00280
76		.00255
77		.00230
78		.00205
79		.00180
80		.00150
81		.00130
82		.00105
83		.00080
84		.00055
85		.00030
86		.00012
87		.00003
88		0

* FORD P/N C8SE-6250-A

Table E-2 - Lift Lobe Data for Regrind of Ford Camshaft* 400 lb/hr Grind

Degrees From ℄	Opening Lift	Closing Lift
0	.03570	.03570
1	▲	▲
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24		
25		
26		
27		
28	▼	▼
29	▲	▲
30		
31		
32		
33		
34		
35		
36		
37		
38		
39		
40		
41	▼	▼
42	.03570	.03570
43	.03560	.03560
44	.03529	.03529
45	.03477	.03477
46	.03404	.03405
47	.03311	.03311
48	.03198	.03198
49	.03063	.03063
50	.02908	.02908
51	.02732	.02732
52	.02536	.02546
53	.02320	.02355
54	.02083	.02164
55	.01851	.01974
56	.01617	.01783
57	.01383	.01593
58	.01152	.01402
59	.00946	.01216
60	.00771	.01050
61	.00627	.00914
62	.00510	.00803
63	.00417	.00714
64	.00344	.00645
65	.00287	.00590
66	.00241	.00547
67	.00200	.00512
68	.00162	.00480
69	.00120	.00450
70	.00080	.00420
71	.00045	.00390
72	.00020	.00360
73	.00005	.00330
74	0	.00305
75		.00280
76		.00255
77		.00230
78		.00205
79		.00180
80		.00155
81		.00130
82		.00105
83		.00080
84		.00055
85		.00033
86		.00012
87		.00002
88		0

* FORD P/N C8SE-6250-A

Table E-3 - Lift Lobe Data for Regrind of Ford Camshaft* 800 lb/hr Grind

Degrees From ℄	Opening Lift	Closing Lift
0	08320	08320
1	↑	↑
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16		
17		
18		
19		
20		
21		
22		
23		
24	↓	
25	.08320	↓
26	.08310	.08320
27	.08279	.08310
28	.08227	.08279
29	.08154	08227
30	.08061	.08155
31	.07945	.08061
32	.07813	.07945
33	.07658	.07812
34	.07482	.07658
35	.07283	.07482
36	.07058	.07286
37	.06823	.07058
38	.06582	.06831
39	.06319	.06573
40	.06047	.06300
41	.05772	.06025
42	.05496	.05750
43	.05221	.05475
44	.04945	.05201
45	.04669	.04926
46	.04394	.04651
47	.04118	.04377
48	.03843	.04102
49	.03567	.03827
50	.03291	.03552
51	.03016	.03278
52	.02740	.03003
53	.02465	.02728
54	.02189	.02454
55	.01914	.02179
56	.01643	.01912
57	.01386	.01625
58	.01152	.01411
59	.00946	.01216
60	.00771	.01050
61	.00627	.00914
62	.00510	.00803
63	.00417	.00714
64	.00344	.00645
65	.00287	.00590
66	.00241	.00547
67	.00200	.00512
68	.00160	.00480
69	.00120	.00450
70	.00080	.00420
71	.00045	.00390
72	.00020	.00360
73	.00005	.00330
74	0	.00305
75		.00280
76		.00255
77		.00230
78		.00205
79		.00180
80		.00155
81		.00130
82		.00105
83		.00080
84		.00055
85		.00030
86		.00012
87		.00002
88		0

* FORD P/N C8SE-6250-A

APPENDIX F

DATA TABULATION

F.1

BASELINE CARBURETOR TESTS

BASELINE EFI TESTS

Speed (rpm)	Torque (bft-lb)	Ignition Timing (°BTDC)	Air/Fuel Ratio	Map (psia)	Exhaust Temp (°F)	BSFC (lb/bhp-hr)	BSNO$_x$	BSCO	BSHC
								gm/bhp-hr	
1200	45	12	20.9	8.5	1205	1.41	0.89	25.2	4.7
1200	100	13	21.4	10.4	1200	0.77	0.59	70.55	2.85
2000	70	37	21.8	7.7	1225	0.8	1.49	7.99	3.61
2000	180	37	21.5	11.2	1280	0.48	2.4	9.65	0.69
640	35	6	13.6	5.5	780	1.45	1.3	131.2	8.2

F.2

SEQUENTIAL INJECTION - I

INJECTOR TIMING 45 DEGREES BTDC

INJECTOR TIMING 90 DEGREES ATDC

INJECTOR TIMING 180 DEGREES ATDC

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTION TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
1	607.5	34.751	0.0	45.8	12.1	5.989	0.0	807.0	1.515	1.551	402.990	26.83
2	604.5	35.970	10.0	45.0	12.1	5.434	0.0	715.0	1.288	1.299	292.426	15.89
3	604.5	35.285	14.3	45.3	12.0	5.136	3.0	1000.0	1.170	1.407	224.276	17.48
4	603.0	34.700	10.0	45.9	15.0	5.641	0.0	778.0	1.114	2.165	13.113	6.09
5	606.0	36.141	21.0	45.7	14.9	5.373	0.0	709.0	1.025	3.039	15.874	9.21
6	609.0	35.704	0.0	46.0	14.9	6.391	0.0	867.0	1.295	2.463	14.756	3.76
7	600.0	34.628	0.0	46.0	20.0	8.965	0.0	1005.0	1.546	0.777	19.567	7.26
8	606.0	35.820	9.7	45.1	19.9	7.474	0.0	851.0	1.194	0.741	12.041	10.38
9	613.5	34.095	14.3	45.4	20.0	7.032	0.0	778.0	1.178	0.680	12.477	21.53
10	640.0	31.949	0.0	90.0	12.0	5.693	0.0	850.0	1.618	1.351	156.038	8.05
11	640.0	31.745	0.0	90.0	14.0	6.309	0.0	872.0	1.616	2.123	33.090	16.88
12	640.0	36.561	0.0	90.0	16.0	7.565	0.0	928.0	1.526	1.525	15.600	1.71
13	640.0	37.604	0.0	90.0	16.0	7.528	0.0	928.0	1.495	1.688	14.660	11.57
14	640.0	33.208	0.0	90.0	18.8	10.215	1.6	985.0	2.105	0.647	37.099	62.45
15	640.0	33.963	10.0	90.0	12.0	5.092	0.0	806.0	1.256	1.203	88.751	10.26
16	640.0	39.639	10.0	90.0	14.0	5.781	0.0	812.0	1.145	1.566	29.063	7.94
17	640.0	38.851	10.0	90.0	16.0	6.735	0.0	828.0	1.255	1.890	13.248	14.64
18	640.0	29.618	10.0	90.0	21.0	9.562	1.0	789.0	1.987	0.358	35.588	125.83
19	640.0	36.540	20.0	90.0	12.0	4.788	0.0	706.0	1.091	1.409	74.157	9.23
20	640.0	35.563	20.0	90.0	14.0	5.226	0.0	708.0	1.098	2.477	17.222	12.70
21	640.0	34.767	20.0	90.0	16.0	5.926	0.0	704.0	1.168	3.133	12.074	26.25
22	640.0	38.393	20.0	90.0	20.5	8.508	0.0	685.0	0.938	0.187	11.607	56.97
23	603.0	35.000	0.0	135.0	12.3	5.818	0.0	823.0	1.400	1.453	252.333	11.01
24	606.0	35.000	4.3	180.0	11.6	5.140	0.0	730.0	1.272	1.668	284.900	14.40
25	607.5	33.000	19.0	180.0	12.5	4.941	0.0	680.0	1.080	1.313	119.561	13.91

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
26	609.0	35.000	0.0	180.0	15.8	6.464	0.0	877.0	1.296	1.687	20.415	7.48
27	607.5	35.000	9.3	180.0	15.3	5.628	0.0	804.0	1.116	1.442	8.807	8.34
28	609.0	35.000	19.7	180.0	15.5	5.280	0.0	745.0	1.017	1.813	11.020	9.62
29	609.0	35.000	0.0	180.0	16.8	9.280	1.5	968.0	1.517	0.617	17.918	6.48
30	609.0	35.000	19.4	180.0	18.7	7.532	1.1	768.0	1.157	0.712	13.608	19.40
31	607.5	35.000	9.1	180.0	18.7	8.020	1.2	835.0	1.250	0.570	13.506	12.06
32	600.0	31.580	0.0	180.0	17.5	7.708	0.5	908.0	1.679	2.630	49.420	57.82
33	600.0	34.729	10.0	180.0	21.9	9.367	1.0	858.0	1.572	0.601	36.695	100.32
34	600.0	29.507	10.0	180.0	19.9	8.277	0.5	900.0	1.743	0.601	38.175	71.99
35	600.0	32.086	20.0	180.0	20.6	7.107	0.2	760.0	1.299	1.021	28.354	65.72
36	1218.0	45.432	40.0	45.0	18.4	5.057	2.0	955.0	0.806	9.388	11.066	6.20
37	1222.5	45.335	25.0	45.0	17.9	5.289	2.4	1045.0	0.880	4.485	10.779	3.35
38	1222.5	46.433	15.0	45.0	17.9	5.649	3.0	1140.0	0.972	3.008	10.322	1.60
39	1222.5	48.096	15.0	45.0	18.0	6.362	3.6	1165.0	0.997	2.228	10.858	1.52
40	1221.0	49.556	25.0	45.0	19.2	5.784	3.0	1065.0	0.829	3.172	11.060	3.53
41	1200.0	47.035	40.0	45.0	19.0	5.485	2.5	965.0	0.826	5.667	10.416	6.95
42	1212.0	47.567	40.2	46.5	23.1	7.671	5.0	925.0	0.959	1.089	15.357	55.24
43	1216.5	43.669	40.6	46.3	21.5	6.822	6.0	985.0	0.947	2.298	15.943	34.34
44	1213.5	47.053	25.6	45.7	21.7	7.346	5.5	1071.0	0.972	1.003	23.409	18.52
45	1213.5	45.757	26.2	45.4	22.8	7.911	5.5	1069.0	1.064	0.887	25.110	38.68
46	1216.5	51.740	15.7	45.4	21.7	8.366	5.5	1205.0	1.053	0.743	24.406	9.25
47	1215.0	50.396	16.5	46.3	22.6	9.068	7.5	1156.0	1.162	0.757	38.951	29.25
48	1204.5	45.000	36.5	90.0	18.0	5.801	2.3	824.0	0.860	10.123	14.661	16.75
49	1213.5	45.000	20.0	90.0	17.7	6.030	2.6	946.0	0.940	4.479	18.485	9.53
50	1198.5	45.000	10.0	90.0	17.9	6.808	3.8	1060.0	1.093	2.437	19.939	4.30

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
51	1204.5	45.000	34.9	90.0	19.8	6.330	3.0	814.0	0.904	5.685	15.486	29.02
52	1212.0	45.000	20.0	90.0	20.0	7.200	4.0	952.0	1.066	2.116	23.310	27.96
53	1213.5	45.000	10.0	90.0	19.7	8.072	6.0	1108.0	1.250	1.219	29.697	12.57
54	1213.5	45.000	35.0	90.0	22.1	7.622	4.5	783.0	1.030	2.824	16.124	68.26
55	1210.5	45.000	20.0	90.0	21.8	8.584	5.8	870.0	1.204	0.949	25.073	79.15
56	1212.0	45.000	10.0	90.0	21.5	9.329	8.0	1109.0	1.347	1.098	37.385	34.54
57	1209.0	43.309	30.0	180.0	19.0	5.504	2.0	988.0	0.834	17.125	9.676	8.70
58	1207.5	46.148	14.8	180.0	18.1	5.452	2.3	1056.0	0.893	7.971	10.114	5.37
59	1209.0	46.532	4.9	180.0	17.7	6.639	3.4	1180.0	1.049	6.712	9.019	2.02
60	1210.5	44.587	29.6	180.0	20.4	5.936	2.5	958.0	0.841	10.386	10.702	8.00
61	1203.0	44.774	14.9	180.0	19.9	6.360	2.8	1051.0	0.931	5.515	11.223	3.52
62	1209.0	45.708	4.0	180.0	19.6	7.291	4.2	1183.0	1.097	4.372	9.929	2.00
63	1221.0	45.000	15.0	180.0	22.4	8.591	6.5	1209.0	1.193	1.117	31.859	11.34
64	1201.0	45.000	30.6	180.0	22.7	7.114	4.0	1001.0	0.950	1.295	18.669	24.54
65	1212.0	45.000	5.0	180.0	21.2	8.900	8.0	1290.0	1.311	0.789	23.021	11.04
66	1204.5	47.291	31.0	180.0	22.8	7.741	5.0	1037.0	1.054	1.009	86.214	62.52
67	1216.5	49.665	15.0	180.0	22.6	8.913	7.5	1284.0	1.202	1.140	45.229	38.77
68	1204.5	48.879	5.0	180.0	21.7	10.548	13.8	1486.0	1.468	0.668	58.458	30.30
69	1212.0	39.384	15.0	180.0	21.4	9.495	13.8	1518.0	1.704	1.010	53.946	28.62
70	1215.0	42.818	17.0	180.0	21.5	7.614	6.0	1287.0	1.235	1.113	40.770	16.82
71	1206.0	43.263	30.2	180.0	21.9	6.730	4.0	1190.0	1.045	1.645	29.259	26.81
72	1222.0	105.254	41.4	47.2	18.7	7.163	4.5	988.0	0.538	16.123	5.949	5.10
73	1219.5	105.256	26.0	46.2	18.4	7.363	5.0	1048.0	0.555	7.706	6.279	3.42
74	1213.5	107.377	11.0	46.0	18.0	7.983	6.0	1195.0	0.620	4.661	8.071	1.37
75	1221.0	104.885	16.0	46.3	17.8	7.390	5.0	1133.0	0.591	6.212	7.747	1.99

	SPEED	TORQUE	IGNITION TIMING	INJECTOR TIMING	AIR/FUEL RATIO	MAP	EXHAUST PRESSURE	EXHAUST TEMP.	BSFC	BSNO	BSCO	BSHC
	(RPM)	(BFT-LB)	(BTDC)	(BTDC)		(PSIA)	(IN-H2O)	(DEG.-F)	(LB/BHP.-R)	-----	(GM/BHP-HR)	------
76	1210.5	104.608	41.6	47.4	19.8	7.454	5.0	977.0	0.538	10.623	5.692	5.57
77	1216.5	107.664	26.3	45.7	19.1	7.739	5.5	1055.0	0.570	5.416	6.708	3.48
78	1218.0	107.567	16.6	46.3	19.8	8.391	7.0	1144.0	0.605	2.776	8.705	1.75
79	1209.0	104.561	41.6	46.9	22.0	8.522	6.5	988.0	0.572	3.384	6.645	10.19
80	1207.5	103.431	25.0	46.1	21.5	9.165	8.0	1089.0	0.638	1.602	8.720	7.97
81	1209.0	104.908	15.0	46.1	20.3	9.600	9.0	1198.0	0.695	1.480	10.470	3.64
82	1210.5	99.217	40.0	46.6	23.9	10.239	9.0	984.0	0.679	0.958	9.194	32.07
83	1213.5	108.616	25.0	46.2	23.5	11.353	16.6	1088.0	0.708	0.784	11.341	25.42
84	1209.0	104.602	15.8	46.6	23.3	13.444	24.0	1140.0	0.872	1.091	22.400	51.91
85	1210.5	101.459	35.7	90.0	18.1	7.356	4.5	1070.0	0.514	18.664	5.193	10.68
86	1218.0	102.468	20.0	90.0	18.1	7.634	5.0	1155.0	0.548	9.662	10.787	3.16
87	1206.0	101.264	10.0	90.0	17.9	8.477	6.5	1240.0	0.629	4.777	8.041	1.31
88	1207.5	101.459	35.0	90.0	19.8	7.887	5.5	1020.0	0.526	10.541	6.594	5.50
89	1213.5	102.506	20.0	90.0	19.4	8.455	6.5	1150.0	0.581	4.593	37.240	2.60
90	1205.0	103.235	9.2	90.0	19.3	9.805	9.0	1240.0	0.681	2.873	14.657	15.86
91	1210.5	102.838	35.0	90.0	23.4	10.660	9.0	985.0	0.624	1.750	7.854	28.63
92	1212.0	105.014	20.0	90.0	22.8	12.367	16.6	1155.0	0.748	1.153	10.841	41.46
93	1215.0	103.850	10.0	90.0	20.0	11.777	16.6	1240.0	0.805	2.652	24.833	44.31
94	1204.5	100.000	30.6	180.0	18.1	7.235	4.0	1017.0	0.531	12.982	5.171	3.89
95	1201.5	100.000	15.1	180.0	17.8	7.685	4.5	1125.0	0.578	4.734	6.840	1.95
96	1209.0	100.000	4.4	180.0	17.7	8.665	7.0	1260.0	0.671	3.445	5.742	0.52
97	1206.0	100.000	30.7	180.0	19.9	7.815	5.0	1017.0	0.537	4.596	5.718	3.80
98	1213.5	100.000	15.3	180.0	19.5	8.663	6.8	1146.0	0.621	2.002	8.206	1.99
99	1206.0	100.000	6.1	180.0	18.8	9.584	9.0	1291.0	0.711	1.987	7.084	0.67
100	1207.5	98.104	28.5	180.0	24.4	11.182	16.6	1074.0	0.725	0.370	16.578	44.78

	SPEED (RPM)	TORQUE (FT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
101	1207.5	99.014	31.1	180.0	23.4	10.106	9.5	1107.0	0.661	0.648	14.518	26.96
102	1206.0	99.027	31.1	180.0	21.6	8.610	7.0	1128.0	0.589	1.947	11.890	8.83
103	1206.0	99.119	15.0	180.0	22.5	11.282	16.6	1330.0	0.763	0.661	22.760	18.54
104	1204.5	99.385	14.7	180.0	21.4	9.818	13.8	1310.0	0.682	0.759	17.929	7.34
105	1204.5	106.088	5.5	180.0	21.6	12.671	24.9	1545.0	0.831	1.250	24.417	20.40

F.3

SEQUENTIAL INJECTION - II

INJECTOR TIMING 45 DEGREES BTDC

INJECTOR TIMING 90 DEGREES ATDC

INJECTOR TIMING 180 DEGREES ATDC

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
1	2000.0	70.349	40.0	45.0	17.9	6.300	8.3	1102.0	0.614	8.295	7.339	1.86
2	2000.0	68.213	40.0	45.0	20.0	6.991	11.0	1107.0	0.643	3.393	9.625	2.35
3	2000.0	63.949	40.0	45.0	24.1	10.112	22.1	994.0	0.851	0.504	12.296	53.43
4	2000.0	74.145	40.0	45.0	22.0	7.966	13.8	1120.0	0.661	1.583	11.882	5.88
5	2000.0	72.556	40.0	45.0	22.0	7.929	13.8	1112.0	0.669	1.567	11.943	6.01
6	2000.0	72.710	25.0	45.0	17.8	6.755	11.0	1174.0	0.652	4.798	6.697	0.68
7	2000.0	70.350	25.0	45.0	20.0	7.787	16.6	1215.0	0.727	1.767	10.065	1.14
8	2000.0	68.964	25.0	45.0	22.4	10.749	30.4	1082.0	1.002	3.687	17.433	59.50
9	2000.0	66.741	15.0	45.0	18.0	7.668	16.6	1323.0	0.820	3.181	5.156	3.00
10	2000.0	74.179	15.0	45.0	20.0	8.351	22.1	1345.0	0.773	1.998	6.018	1.26
11	2000.0	70.000	40.0	90.0	18.4	5.600	8.3	1038.0	0.588	16.981	7.800	4.80
12	2000.0	67.383	40.0	90.0	20.0	6.200	11.0	1076.0	0.647	5.764	11.106	4.13
13	2000.0	70.512	40.0	90.0	24.6	8.900	22.1	946.0	0.798	0.210	12.064	54.09
14	2000.0	70.700	40.0	90.0	22.0	7.000	16.6	1061.0	0.656	2.587	13.535	9.76
15	2000.0	70.715	25.0	90.0	18.0	6.200	13.8	1158.0	0.674	4.748	8.525	1.66
16	2000.0	69.688	25.0	90.0	20.5	7.100	16.6	1220.0	0.729	1.818	13.696	2.04
17	2000.0	70.659	25.0	90.0	24.5	9.200	27.6	1082.0	0.833	0.412	15.367	54.52
18	2000.0	70.000	25.0	90.0	22.4	7.600	22.1	1164.0	0.728	0.963	14.428	9.14
19	2000.0	68.525	15.0	90.0	18.0	6.500	16.6	1000.0	0.755	2.103	5.833	0.74
20	2000.0	68.540	15.0	90.0	19.8	7.200	20.7	1332.0	0.792	1.965	6.304	0.38
21	2000.0	72.002	15.0	90.0	22.8	9.100	30.4	1418.0	0.886	0.606	14.678	1.43
22	2000.0	75.975	15.0	90.0	24.0	11.752	41.5	990.0	0.953	0.899	81.868	51.42
23	2000.0	75.014	15.0	90.0	22.0	8.650	19.3	1220.0	0.722	0.712	15.117	5.77
24	2000.0	67.899	40.0	180.0	18.0	5.654	8.3	1118.0	0.626	10.511	8.463	1.78
25	2000.0	69.773	40.0	180.0	20.0	6.285	11.0	1120.0	0.641	5.640	10.506	1.98

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
26	2000.0	67.736	40.0	180.0	25.2	9.834	24.9	985.0	0.897	0.527	13.292	63.34
27	2000.0	73.445	40.0	180.0	24.0	8.112	19.3	1107.0	0.715	0.926	13.759	18.69
28	2000.0	70.968	40.0	180.0	22.0	7.059	16.6	1123.0	0.658	1.483	11.976	5.03
29	2000.0	69.370	25.0	180.0	18.0	5.848	11.0	1212.0	0.685	7.456	6.682	0.63
30	2000.0	64.057	25.0	180.0	20.0	6.704	13.8	1223.0	0.771	2.981	9.574	0.86
31	2000.0	69.180	25.0	180.0	24.2	10.140	27.6	1152.0	0.962	0.763	21.143	56.91
32	2000.0	71.558	25.0	180.0	22.0	7.488	16.6	1242.0	0.750	1.432	12.479	2.26
33	2000.0	69.928	15.0	180.0	18.0	6.403	13.8	1292.0	0.766	3.946	3.895	0.32
34	2000.0	73.100	15.0	180.0	20.0	7.556	19.3	1332.0	0.790	1.989	4.911	0.27
35	2000.0	73.120	15.0	180.0	23.5	10.983	44.2	1412.0	1.040	0.519	27.118	28.99
36	2000.0	69.165	15.0	180.0	22.0	8.935	27.6	1403.0	0.912	0.869	10.983	1.49
37	2000.0	178.892	40.0	45.0	18.0	9.794	24.9	1195.0	0.426	18.137	4.459	2.75
38	2000.0	180.092	40.0	45.0	20.0	10.642	33.2	1162.0	0.412	10.609	5.000	2.20
39	2000.0	178.651	40.0	45.0	23.5	13.839	60.9	1173.0	0.501	1.400	5.860	14.22
40	2000.0	198.312	40.0	45.0	24.1	15.175	69.2	1134.0	0.470	1.392	5.229	16.04
41	2000.0	187.537	40.0	45.0	22.0	12.437	49.8	1198.0	0.433	3.151	5.412	4.10
42	2000.0	179.284	25.0	45.0	18.0	10.298	33.2	1253.0	0.441	8.830	5.578	1.32
43	2000.0	180.047	25.0	45.0	20.0	11.500	44.3	1280.0	0.453	3.764	6.443	1.06
44	2000.0	176.887	25.0	45.0	22.3	14.218	69.2	1342.0	0.532	1.185	9.208	5.43
45	2000.0	186.937	15.0	45.0	20.0	12.698	49.8	1420.0	0.487	4.012	6.742	-0.70
46	2000.0	181.632	15.0	45.0	18.0	12.620	49.8	1360.0	0.512	3.355	5.348	0.88
47	2000.0	174.959	40.0	90.0	17.9	9.618	27.7	1193.0	0.430	18.116	4.620	2.47
48	2000.0	181.166	40.0	90.0	20.0	10.668	36.0	1185.0	0.434	10.613	5.632	2.13
49	2000.0	183.242	40.0	90.0	24.2	14.981	71.9	1130.0	0.516	1.413	6.653	21.41
50	2000.0	179.429	25.0	90.0	17.9	9.923	33.2	1280.0	0.435	10.060	6.100	1.77

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
51	2000.0	183.268	25.0	90.0	20.0	11.914	49.8	1303.0	0.466	3.505	7.673	1.47
52	2000.0	184.151	25.0	90.0	22.3	14.983	77.5	1345.0	0.543	1.313	10.742	7.81
53	2000.0	184.263	15.0	90.0	18.0	11.137	44.3	1403.0	0.483	6.091	6.072	0.31
54	2000.0	181.273	35.0	180.0	18.0	9.196	24.9	1220.0	0.418	17.868	4.503	2.01
55	2000.0	182.386	35.0	180.0	20.0	9.747	27.6	1196.0	0.413	14.339	5.414	1.76
56	2000.0	174.456	35.0	180.0	25.5	14.165	66.4	1208.0	0.532	0.917	6.888	19.65
57	2000.0	188.501	35.0	180.0	24.0	13.353	60.8	1243.0	0.467	0.931	5.998	7.39
58	2000.0	183.544	35.0	180.0	22.0	11.372	44.2	1226.0	0.433	3.264	6.425	2.26
59	2000.0	180.853	25.0	180.0	17.1	9.493	27.6	1258.0	0.430	12.146	5.099	1.16
60	2000.0	181.110	25.0	180.0	20.0	10.221	35.9	1256.0	0.432	7.812	6.442	0.81
61	2000.0	175.883	25.0	180.0	24.5	15.169	74.7	1310.0	0.557	0.721	11.241	12.11
62	2000.0	179.525	25.0	180.0	22.0	11.772	44.2	1271.0	0.475	2.363	7.628	1.43
63	2000.0	179.201	20.0	180.0	18.0	9.823	27.6	1252.0	0.459	9.027	5.666	1.16
64	2000.0	181.952	20.0	180.0	20.0	10.795	38.7	1307.0	0.460	5.175	6.723	0.59

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*                                               *
*                     F.4                       *
*              IGNITION EFFECTS                 *
*                                               *
*                                               *
*                                               *
*   A   STD. GAP (.035) - STD. ENERGY/DURATION  *
*                                               *
*   B   STD. GAP        -  #2  ENERGY/DURATION  *
*                                               *
*   C   STD. GAP        -  #3  ENERGY/DURATION  *
*                                               *
*   D        GAP (.045)                         *
*                                               *
*   E        GAP (.060)                         *
*                                               *
*                                               *
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	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
1	640.5	37.586	0.0	44.7	11.9	A	6.002	0.0	815.0	1.230	1.418	66.058	6.59
2	646.5	38.335	10.0	44.9	12.0	A	5.546	0.0	747.0	1.149	1.744	26.764	6.37
3	627.0	35.940	20.0	43.7	12.2	A	5.200	0.0	691.0	1.039	1.577	14.282	8.71
4	643.5	36.665	0.0	45.6	15.1	A	7.279	0.5	892.0	1.388	1.000	8.676	3.89
5	643.5	34.975	10.0	45.1	15.1	A	6.305	0.2	780.0	1.200	0.454	8.058	6.91
6	645.0	35.121	20.0	45.0	15.1	A	5.970	0.3	728.0	1.082	0.520	8.378	8.77
7	645.0	37.033	0.0	44.8	15.5	A	7.543	0.6	886.0	1.414	0.732	11.520	3.77
8	645.0	36.748	10.0	45.3	17.6	A	7.453	0.7	824.0	1.251	0.355	13.364	12.36
9	646.5	35.344	20.0	45.3	19.1	A	7.546	0.8	752.0	1.227	0.400	15.703	41.23
10	646.5	32.762	0.0	45.1	12.0	B	6.048	0.1	794.0	1.473	1.398	212.869	10.29
11	645.0	35.845	10.0	45.0	11.8	B	5.369	3.0	0.0	1.147	1.155	82.962	8.84
12	643.5	36.079	20.0	44.3	12.0	B	5.076	0.0	615.0	1.003	1.246	62.506	10.49
13	643.5	33.696	0.0	44.8	15.0	B	6.988	0.5	815.0	1.433	1.379	16.402	12.56
14	644.5	34.331	10.0	44.5	15.0	B	5.983	0.3	718.0	1.130	0.477	10.994	11.14
15	640.5	34.903	20.0	44.4	15.0	B	5.587	0.0	651.0	1.003	1.135	10.335	11.32
16	642.0	33.034	0.0	45.0	18.0	B	8.605	1.1	895.0	1.626	0.577	21.184	23.36
17	643.5	31.924	10.0	45.2	18.2	B	7.314	0.9	772.0	1.339	0.414	15.275	21.30
18	643.5	34.815	20.0	44.7	18.6	B	6.861	0.5	720.0	1.099	0.327	12.300	18.71
19	640.0	36.769	0.0	36.6	12.0	C	8.025	0.0	718.0	1.279	1.159	242.354	9.28
20	640.0	32.128	10.0	33.1	12.0	C	8.048	0.0	680.0	1.264	1.113	176.925	10.18
21	640.0	31.399	20.0	32.4	11.9	C	8.022	0.0	620.0	1.153	1.144	122.920	13.05
22	640.0	36.214	0.0	27.2	15.0	C	8.019	0.0	760.0	1.232	1.323	8.021	4.92
23	640.0	33.309	10.0	31.0	14.9	C	8.011	0.0	713.0	1.121	1.118	8.118	6.42
24	640.0	36.489	20.0	26.0	15.0	C	8.007	0.0	655.0	0.929	1.466	8.223	6.85
25	640.0	37.867	0.0	45.0	32.4	C	7.934	3.2	970.0	1.615	0.745	40.453	64.72

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
26	639.0	37.815	0.0	44.4	20.0	C	7.940	2.0	925.0	1.378	0.743	19.151	29.79
27	637.5	32.617	10.0	44.5	22.9	C	7.935	2.2	800.0	1.539	0.732	28.720	100.46
28	646.5	34.514	10.0	45.3	20.0	C	7.939	1.0	810.0	1.244	0.059	13.960	28.74
29	645.0	40.509	20.0	44.6	22.5	C	7.940	1.5	700.0	1.108	0.318	16.106	71.14
30	643.5	34.625	20.0	44.5	20.0	C	7.921	0.8	727.0	1.069	0.134	12.872	24.40
31	643.5	36.508	0.0	44.6	11.9	D	8.011	0.2	745.0	1.255	1.129	180.904	8.57
32	649.5	36.990	10.0	44.8	12.1	D	7.968	0.0	706.0	1.077	0.996	119.362	8.42
33	643.5	35.516	20.0	44.1	12.0	D	7.971	0.0	626.0	0.965	1.067	75.385	11.29
34	648.0	36.916	0.0	44.7	15.0	D	7.976	0.5	810.0	1.173	1.377	7.451	4.87
35	646.5	36.201	10.0	44.4	15.0	D	7.964	0.3	712.0	0.990	1.149	6.899	7.46
36	646.5	35.916	20.0	44.6	15.0	D	7.955	0.0	660.0	0.891	1.422	7.874	7.05
37	645.0	32.424	0.0	45.0	22.3	D	7.951	2.5	972.0	1.767	0.480	45.768	50.21
38	640.0	35.000	10.0	45.0	22.2	D	8.380	1.8	815.0	1.407	1.087	42.301	40.47
39	649.5	36.456	10.0	44.4	20.0	D	7.953	1.4	810.0	1.261	0.209	14.699	39.68
40	658.5	34.353	20.0	44.6	21.7	D	7.950	1.3	670.0	1.187	0.227	14.829	78.34
41	660.0	32.021	20.0	45.8	20.0	D	7.940	1.0	680.0	1.217	0.204	13.687	53.16
42	651.0	34.891	0.0	41.4	12.2	E	5.870	0.0	715.0	1.328	0.978	259.835	9.68
43	649.5	38.158	0.0	41.1	15.0	E	6.422	0.0	770.0	1.147	1.295	8.590	32.05
44	649.5	38.173	0.0	40.1	19.1	E	8.451	1.0	872.0	1.301	0.331	14.818	5.30
45	645.0	35.576	0.0	40.4	21.9	E	10.719	2.3	945.0	1.696	0.445	34.840	35.81
46	642.0	37.702	10.0	41.2	12.0	E	5.324	0.0	682.0	1.058	0.839	147.435	9.63
47	648.0	38.973	10.0	40.8	15.0	E	5.808	0.0	730.0	0.938	1.033	6.659	4.65
48	652.5	43.135	10.0	40.0	23.9	E	10.911	2.2	750.0	1.306	0.676	22.297	99.23
49	643.5	37.698	10.0	39.8	22.0	E	9.102	1.3	807.0	1.273	0.524	21.269	59.16
50	643.5	36.448	20.0	40.5	12.0	E	5.015	0.0	621.0	1.001	0.862	12.767	12.34

	SPEED (RPM)	TORQUE (BFT•LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN•H2O)	EXHAUST TEMP. (DEG••F)	BSFC (LB/BHP•HR)	BSNO •••••	BSCO (GM/BHP•HR)	BSHC ••••••
51	643•5	37•001	20•0	40•5	15•0	E	5•487	0•0	662•0	0•926	1•085	9•078	7•95
52	642•0	37•990	20•0	40•3	22•2	E	9•051	1•2	627•0	1•221	0•555	18•319	88•84
53	642•0	37•447	20•0	40•2	22•0	E	8•018	0•7	666•0	1•096	0•458	15•054	65•63
54	1209•0	46•717	35•0	45•2	18•0	A	5•589	2•5	914•0	0•771	3•958	10•007	5•94
55	1216•5	49•155	40•0	45•2	18•2	A	5•635	2•4	902•0	0•767	5•795	10•075	9•43
56	1210•5	47•336	25•0	45•2	18•0	A	5•776	2•6	978•0	0•826	2•240	10•538	3•29
57	1209•0	45•409	15•0	45•3	18•0	A	6•201	2•6	1036•0	0•916	1•720	10•775	2•08
58	1212•0	46•623	35•0	45•5	20•0	A	6•309	3•5	951•0	0•823	2•910	11•840	8•08
59	1210•5	43•687	40•0	47•4	20•0	A	6•316	3•5	937•0	0•875	1•975	12•067	16•67
60	1212•0	48•266	25•0	43•6	20•0	A	6•671	3•7	995•0	0•886	1•395	13•776	5•63
61	1213•5	47•490	15•0	45•1	20•0	A	7•394	5•0	956•0	1•005	1•197	16•451	40•02
62	1213•5	43•045	35•0	44•8	22•8	A	8•117	5•5	1000•0	1•087	0•501	21•161	62•42
63	1210•5	45•875	40•0	45•3	22•7	A	8•201	5•7	1000•0	1•023	0•697	17•379	68•48
64	1209•0	47•489	25•0	45•1	22•6	A	8•264	6•0	1000•0	1•002	0•753	23•458	40•70
65	1209•0	48•951	15•0	45•0	21•2	A	8•234	6•3	1000•0	1•022	0•876	22•335	7•98
66	1209•0	47•178	35•0	45•1	18•0	B	5•525	2•5	917•0	0•746	3•168	9•449	5•71
67	1210•5	45•847	40•0	44•8	17•9	B	5•497	2•5	912•0	0•752	3•189	9•301	5•54
68	1209•0	46•582	25•0	44•8	18•0	B	5•804	3•0	981•0	0•813	1•648	10•102	4•12
69	1206•0	51•676	15•0	45•0	18•1	B	6•008	3•3	1032•0	0•761	1•595	9•373	2•69
70	1218•0	48•935	35•0	[illegible]	19•7	B	6•442	3•6	962•0	0•848	1•264	13•194	8•09
71	1213•5	45•162	25•0	44•9	19•7	B	6•792	4•2	1040•0	0•929	0•725	14•630	6•20
72	1215•0	48•811	15•0	[illegible]	20•0	B	7•050	4•9	1092•0	0•946	1•020	13•239	2•92
73	1209•0	44•022	40•0	44•9	20•2	B	6•307	3•6	934•0	0•845	1•365	13•372	13•18
74	1221•0	45•720	35•0	45•1	23•0	B	7•697	5•5	910•0	0•941	0•722	17•104	48•91
75	1212•0	44•889	40•0	44•4	[illegible]	-	7•674	5•3	875•0	0•948	0•395	16•810	54•26

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
76	1209.0	44.123	40.0	44.7	21.9	B	6.937	4.0	900.0	0.880	0.751	14.925	26.71
77	1215.0	57.382	25.0	45.5	22.9	B	8.839	7.0	960.0	0.890	0.760	17.838	45.32
78	1209.0	45.013	15.0	45.1	22.7	B	9.046	7.5	1074.0	1.151	0.031	34.290	47.53
79	1210.5	44.056	35.0	44.7	18.0	C	5.297	2.5	870.0	0.724	5.480	9.339	4.84
80	1215.0	44.710	40.0	45.3	18.0	C	5.295	2.5	865.0	0.713	5.422	8.981	4.72
81	1215.0	43.979	25.0	45.0	18.0	C	5.499	2.8	936.0	0.779	2.383	9.769	3.60
82	1209.0	42.923	15.0	44.7	18.0	C	5.835	3.0	1009.0	0.849	1.679	8.893	2.29
83	1215.0	44.774	35.0	45.0	20.0	C	5.860	2.7	903.0	0.750	1.855	10.095	6.25
84	1210.5	43.133	40.0	44.8	20.0	C	5.860	2.6	890.0	0.776	2.492	10.536	7.36
85	1207.5	43.950	25.0	44.6	19.9	C	6.031	3.0	965.0	0.804	1.115	11.472	4.59
86	1210.5	45.405	15.0	44.4	19.8	C	6.867	4.2	1055.0	0.921	0.615	13.038	3.44
87	1212.0	42.184	35.0	44.9	23.6	C	7.884	5.0	869.0	0.994	0.552	17.967	64.24
88	1215.0	42.442	35.0	44.8	22.0	C	6.934	3.8	930.0	0.898	0.348	16.668	24.10
89	1212.0	42.696	40.0	44.7	23.7	C	7.901	5.0	860.0	0.973	0.200	16.064	68.14
90	1213.5	44.424	40.0	45.0	22.0	C	6.780	3.9	910.0	0.832	0.690	14.688	18.77
91	1213.5	47.784	25.0	45.0	23.1	C	8.329	6.0	980.0	0.952	1.378	21.514	49.73
92	1215.0	45.091	25.0	45.1	22.0	C	7.296	4.5	990.0	0.897	0.584	18.429	16.60
93	1210.5	43.156	15.0	45.2	22.1	C	8.235	6.2	1082.0	1.086	0.522	26.052	12.79
94	1209.0	43.509	15.0	44.9	23.5	C	9.569	8.0	1028.0	1.213	0.873	34.595	73.06
95	1209.0	44.781	40.0	45.0	18.0	D	5.366	2.2	880.0	0.767	3.446	9.781	5.01
96	1212.0	46.954	40.0	45.0	20.0	D	6.031	3.0	912.0	0.762	1.316	10.204	8.80
97	1215.0	44.547	40.0	45.0	22.9	D	7.610	4.8	872.0	0.941	0.344	15.264	62.42
98	1209.0	44.367	40.0	45.0	22.0	D	7.089	4.1	895.0	0.896	0.511	15.788	36.48
99	1218.0	42.082	25.0	45.0	18.0	D	5.488	2.3	926.0	0.841	1.288	10.093	4.82
100	1204.5	44.405	25.0	45.0	20.0	D	6.464	3.4	980.0	0.876	0.689	13.891	7.88

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
101	1210.5	43.367	25.0	45.0	22.9	D	8.159	5.7	945.0	1.051	0.505	23.319	61.07
102	1212.0	46.484	25.0	45.0	22.0	D	6.959	4.5	973.0	0.861	0.685	17.626	16.03
103	1210.5	46.415	15.0	45.0	18.0	D	5.911	3.0	1022.0	0.866	1.181	10.003	2.49
104	1212.0	46.116	15.0	45.0	20.0	D	6.785	4.1	1070.0	0.937	0.764	15.046	3.54
105	1209.0	42.770	15.0	45.0	23.2	D	9.409	8.0	1061.0	1.285	0.604	44.373	72.23
106	1209.0	44.335	15.0	45.0	22.0	D	8.021	6.0	1113.0	1.092	0.622	28.999	16.16
107	1209.0	47.530	35.0	42.2	18.0	E	5.393	2.0	865.0	0.740	3.766	8.848	4.60
108	1203.0	44.862	35.0	42.6	20.0	E	5.933	2.6	885.0	0.807	1.752	11.183	7.54
109	1215.0	52.598	35.0	41.7	24.4	E	8.525	5.7	840.0	0.899	0.359	14.530	61.33
110	1201.5	45.815	35.0	41.9	22.0	E	6.871	3.6	904.0	0.818	0.892	13.742	20.51
111	1206.0	46.245	40.0	42.1	18.0	E	5.305	2.1	842.0	0.707	5.798	9.045	4.69
112	1209.0	46.630	40.0	42.1	20.0	E	5.815	2.6	861.0	0.731	3.106	9.692	7.06
113	1207.5	50.305	40.0	41.4	24.6	E	8.203	5.4	821.0	0.865	0.419	12.925	59.01
114	1204.5	45.225	40.0	41.4	22.0	E	6.555	3.5	879.0	0.804	1.119	12.864	17.75
115	1204.5	46.123	25.0	41.5	18.0	E	5.569	2.2	912.0	0.776	2.350	8.979	3.47
116	1207.5	45.356	25.0	41.7	20.0	E	6.212	2.8	952.0	0.819	1.134	11.194	5.36
117	1212.0	46.983	25.0	41.0	24.1	E	8.721	6.0	896.0	1.009	0.396	19.181	67.16
118	1215.0	46.850	25.0	41.4	22.0	E	7.297	3.0	4.5	0.876	0.567	16.085	18.78
119	1212.0	46.659	15.0	41.5	18.0	E	5.956	2.5	992.0	0.833	1.388	9.003	2.34
120	1210.5	45.726	15.0	41.4	20.0	E	6.867	3.8	1037.0	0.922	0.839	12.718	3.57
121	1212.0	44.062	15.0	41.6	23.5	E	9.520	7.9	1045.0	1.269	0.638	44.517	73.16
122	1203.0	46.589	15.0	41.3	22.0	E	7.932	5.6	1085.0	1.011	0.566	23.136	8.94
123	1210.5	101.557	35.0	46.2	18.3	A	7.411	5.0	1005.0	0.496	11.202	5.139	3.87
124	1210.5	103.151	40.0	45.9	18.3	A	7.425	5.0	996.0	0.486	14.843	4.897	4.08
125	1209.0	101.074	25.0	45.5	18.0	A	7.588	5.4	1057.0	0.520	5.529	6.617	2.81

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
126	1212.0	103.500	15.0	45.6	18.0	A	8.093	6.0	1132.0	0.550	3.387	7.320	1.75
127	1218.0	104.815	35.0	45.5	19.7	A	8.163	6.2	1018.0	0.510	4.592	5.762	4.02
128	1209.0	101.439	40.0	45.8	20.1	A	8.104	6.2	1000.0	0.497	4.350	5.417	4.68
129	1209.0	104.696	25.0	45.2	20.2	A	8.683	7.0	1070.0	0.526	1.779	6.463	3.52
130	1213.5	102.852	15.0	45.4	19.8	A	9.187	8.0	1142.0	0.582	1.125	8.386	2.49
131	1210.5	97.986	35.0	45.1	24.0	A	11.069	10.0	960.0	0.634	0.482	9.323	35.84
132	1209.0	103.582	40.0	45.2	22.1	A	9.415	9.0	992.0	0.537	1.050	6.746	11.75
133	1209.0	99.884	40.0	45.7	24.1	A	11.578	16.6	911.0	0.654	0.201	9.556	43.52
134	1215.0	110.785	25.0	45.1	23.4	A	11.723	19.3	1047.0	0.620	0.541	10.017	25.46
135	1207.5	102.045	25.0	45.6	21.6	A	9.382	8.0	1054.0	0.563	1.100	7.975	7.74
136	1209.0	109.446	15.0	44.8	22.6	A	11.259	22.1	1149.0	0.642	0.670	13.921	8.65
137	1209.0	102.657	35.0	45.1	22.0	A	9.592	8.2	993.0	0.558	0.984	7.721	10.96
138	1209.0	101.772	35.0	45.5	17.8	B	7.313	4.5	943.0	0.484	10.921	4.295	4.29
139	1212.0	100.368	40.0	45.4	18.0	B	7.281	4.4	920.0	0.486	13.625	4.234	4.41
140	1209.0	101.662	25.0	45.3	17.9	B	7.509	4.7	995.0	0.500	5.592	5.061	2.97
141	1207.5	101.797	15.0	45.7	17.9	B	7.971	5.6	1080.0	0.547	3.556	6.593	1.91
142	1210.5	102.089	35.0	45.7	20.0	B	7.947	5.5	950.0	0.493	4.211	4.960	4.39
143	1210.5	100.839	40.0	45.5	20.0	B	7.946	5.5	934.0	0.489	4.791	4.789	4.88
144	1209.0	101.935	25.0	45.2	20.0	B	8.315	6.0	1005.0	0.511	1.857	5.754	3.71
145	1209.0	101.604	15.0	45.5	20.0	B	8.830	7.0	1071.0	0.564	1.206	7.328	26.19
146	1213.5	102.066	35.0	44.4	24.3	B	11.172	13.8	920.0	0.615	0.154	8.580	35.15
147	1210.5	102.105	35.0	45.6	22.2	B	9.118	7.0	960.0	0.526	1.167	6.197	9.41
148	1215.0	101.654	40.0	45.5	24.6	B	11.278	13.8	881.0	0.613	0.445	8.451	42.55
149	1212.0	100.461	40.0	45.5	22.0	B	8.884	6.8	944.0	0.517	1.525	6.079	9.42
150	1210.5	103.531	25.0	45.7	24.3	B	12.404	16.6	978.0	0.679	0.580	11.595	44.51

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
151	1207.5	99.944	25.0	45.3	22.0	B	9.331	7.5	1016.0	0.567	1.003	8.133	8.32
152	1218.0	104.981	15.0	45.9	23.5	B	12.752	22.1	1109.0	0.721	0.498	15.308	34.18
153	1210.5	106.901	15.0	44.6	22.0	B	10.641	15.2	1102.0	0.613	0.684	10.803	8.83
154	1216.5	100.295	35.0	44.8	18.0	C	8.024	4.5	934.0	0.474	14.009	4.764	4.16
155	1209.0	101.238	39.8	44.3	18.0	C	8.021	4.6	927.0	0.477	17.288	4.242	4.20
156	1201.5	101.210	25.0	44.3	18.0	C	8.021	4.8	980.0	0.496	1.091	5.160	2.95
157	1210.5	99.190	15.0	44.4	17.6	C	8.027	5.8	1064.0	0.561	3.978	6.441	1.57
158	1207.5	101.709	35.0	44.3	20.0	C	8.026	5.4	945.0	0.473	6.060	4.897	3.99
159	1209.0	102.595	40.0	44.4	20.0	C	8.034	5.5	925.0	0.475	6.590	4.739	4.11
160	1209.0	101.737	25.0	44.6	20.0	C	8.040	6.0	950.0	0.522	2.418	5.890	3.19
161	1210.5	100.046	15.0	44.4	20.0	C	8.023	8.0	1102.0	0.593	1.331	8.016	1.78
162	1212.0	100.409	35.0	44.0	24.7	C	8.016	13.8	845.0	0.647	0.259	9.373	41.91
163	1215.0	102.372	35.0	44.3	22.0	C	8.024	6.3	952.0	0.512	1.801	5.751	6.94
164	1228.5	101.343	40.0	45.5	25.1	C	8.021	16.2	867.0	0.642	0.321	9.494	45.61
165	1209.0	103.048	40.0	44.1	24.1	C	8.032	13.5	905.0	0.586	0.531	7.909	26.94
166	1207.5	102.527	40.0	44.0	21.9	C	8.017	6.2	931.0	0.517	2.074	5.876	7.97
167	1215.0	104.842	25.0	44.3	24.1	C	8.017	16.2	984.0	0.698	0.410	11.506	38.28
168	1209.0	99.876	25.0	43.8	22.0	C	8.025	8.0	1032.0	0.581	1.018	8.557	7.21
169	1207.5	100.408	40.0	45.0	18.0	D	7.007	4.0	923.0	0.482	11.148	4.087	3.85
170	1207.5	100.853	40.0	45.0	20.0	D	7.731	4.8	930.0	0.491	3.820	4.627	4.74
171	1210.5	101.402	25.0	45.0	18.0	D	7.375	4.4	965.0	0.506	4.182	4.872	3.05
172	1210.5	101.343	25.0	45.0	20.0	D	8.160	5.7	1004.0	0.524	1.568	5.890	3.65
173	1212.0	100.624	15.0	45.0	18.0	D	7.785	5.4	1077.0	0.555	2.439	6.419	1.55
174	1212.0	101.690	15.0	45.0	20.0	D	8.992	7.5	1117.0	0.585	0.820	7.589	2.10
175	1219.5	103.442	35.0	44.8	25.2	D	7.972	16.6	890.0	0.620	0.181	8.456	40.24

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
176	1215.0	106.485	35.0	44.4	24.0	D	7.933	9.0	932.0	0.558	0.604	6.613	22.28
177	1209.0	96.220	35.0	44.6	22.0	D	7.856	6.5	950.0	0.513	1.141	5.040	7.79
178	1209.0	95.843	40.0	44.9	24.8	D	7.856	13.8	837.0	0.655	0.069	8.041	47.97
179	1210.5	95.420	40.0	44.0	22.0	D	7.850	6.5	924.0	0.523	1.255	4.776	9.70
180	1219.5	97.812	25.0	44.7	24.5	D	7.938	23.5	940.0	0.730	0.239	10.749	51.12
181	1218.0	100.227	25.0	45.1	22.0	D	7.938	8.0	1015.0	0.583	0.858	7.562	10.75
182	1215.0	94.783	15.0	44.2	23.7	D	7.856	24.9	1080.0	0.812	0.283	15.756	46.78
183	1215.0	91.557	15.0	44.3	22.0	D	7.854	13.8	1060.0	0.720	0.469	11.947	19.35
184	1216.5	100.675	35.0	41.8	18.0	E	7.189	4.0	920.0	0.481	9.362	4.324	3.60
185	1212.0	101.481	35.0	41.7	20.0	E	7.676	4.5	918.0	0.495	5.389	4.894	4.20
186	1213.5	99.857	35.0	40.0	25.4	E	12.076	13.8	822.0	0.669	0.398	11.183	50.07
187	1215.0	102.270	35.0	40.6	24.0	E	10.288	8.5	917.0	0.578	0.718	8.114	25.24
188	1212.0	100.395	35.0	41.4	22.0	E	8.547	6.2	934.0	0.519	1.646	5.884	7.01
189	1215.0	101.502	40.0	41.7	18.0	E	7.070	4.0	895.0	0.485	16.319	4.280	4.01
190	1213.5	100.447	40.0	42.1	20.0	E	7.566	4.5	900.0	0.485	6.891	4.765	4.40
191	1209.0	90.654	40.0	41.4	25.5	E	11.710	10.0	793.0	0.724	0.578	11.751	56.16
192	1210.5	102.550	40.0	41.4	24.9	E	10.058	8.0	889.0	0.554	0.625	7.633	24.48
193	1213.5	102.309	40.0	41.7	22.2	E	8.197	5.8	906.0	0.491	3.092	5.413	6.61
194	1210.5	102.195	25.0	42.0	18.0	E	7.251	4.2	945.0	0.511	7.023	5.214	3.30
195	1213.5	104.089	25.0	42.2	20.0	E	7.824	5.0	958.0	0.502	3.736	5.768	3.37
196	1213.5	99.915	25.0	41.3	25.0	E	11.885	16.6	938.0	0.686	1.274	11.906	43.67
197	1216.5	101.255	25.0	41.1	24.0	E	10.509	9.8	980.0	0.608	0.684	9.024	19.12
198	1212.0	100.104	25.0	40.8	22.0	E	9.179	7.5	1004.0	0.559	0.491	7.546	7.69
199	1215.0	102.133	15.0	40.6	18.0	E	7.501	5.0	1030.0	0.533	4.540	6.120	1.86
200	1216.5	102.401	15.0	40.1	20.1	E	8.476	6.4	1058.0	0.568	2.084	7.435	1.96

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (B.DC)	AIR/FUEL RATIO	IGNITION EFFECT (SPARK)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
201	1203.0	97.680	15.0	40.6	23.9	E	12.462	19.3	1092.0	0.762	0.534	15.597	32.55
202	1207.5	102.126	15.0	39.8	22.2	E	10.016	9.3	1105.0	0.618	0.779	10.244	5.23

F.5

INLET AIR HEATING

	SPEED (RPM)	TORQUE (BFT.LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN.H2O)	EXHAUST TEMP. (DEG.F)	BSFC (LB/BHP.HR)	BSNO -----	BSCO (GM/BHP.HR)	BSHC ------
1	655.5	37.548	20.0	40.2	12.0	100	4.813	0.0	690.0	0.962	1.367	60.183	8.76
2	643.5	32.612	20.0	39.6	14.0	100	5.068	0.0	694.0	0.918	1.035	[illegible].409	6.50
3	663.0	34.291	20.0	42.2	16.0	100	5.377	0.0	696.0	0.920	0.666	8.924	7.66
4	679.5	37.072	20.0	42.1	18.0	100	6.132	0.0	710.0	0.890	0.154	8.784	12.31
5	640.0	41.488	20.0	50.3	22.8	100	8.955	0.0	670.0	1.107	0.276	14.838	73.41
6	640.0	39.403	10.0	45.4	12.0	100	5.189	0.0	735.0	0.936	1.125	30.819	6.79
7	649.5	36.617	10.0	39.8	14.0	100	5.391	0.0	747.0	0.939	0.888	7.267	5.59
8	645.0	35.441	10.0	39.8	16.0	100	5.946	0.0	748.0	0.988	0.215	8.290	7.69
9	661.5	34.726	10.0	40.7	18.0	100	6.319	0.0	763.0	0.972	0.144	9.083	9.85
10	672.0	37.159	10.0	42.3	22.6	100	9.321	0.0	755.0	1.246	0.281	18.565	77.29
11	655.5	37.967	0.0	40.7	12.0	100	5.586	0.0	815.0	1.173	1.147	128.119	8.21
12	649.5	34.407	0.0	40.7	14.0	100	5.826	0.0	838.0	1.210	1.317	9.859	4.13
13	651.0	33.197	0.0	40.9	16.0	100	6.544	0.0	860.0	1.295	0.524	9.885	4.22
14	649.5	33.674	0.0	41.1	18.0	100	7.457	0.0	900.0	1.364	0.294	13.634	6.30
15	643.5	31.564	0.0	41.3	22.1	100	10.919	0.0	950.0	1.960	0.543	40.172	78.00
16	651.0	35.029	0.0	42.6	12.0	150	5.604	0.0	841.0	1.283	1.336	78.239	7.18
17	651.0	32.560	0.0	42.3	14.0	150	6.186	0.0	840.0	1.298	1.011	9.062	3.91
18	654.0	36.855	0.0	43.1	16.0	150	6.881	0.0	865.0	1.253	0.462	9.868	4.43
19	654.0	37.572	0.0	42.5	18.0	150	8.211	0.0	930.0	1.327	0.217	14.662	10.14
20	651.0	34.294	0.0	42.8	22.4	150	12.076	0.0	890.0	1.891	0.705	38.831	109.15
21	649.5	35.262	10.0	42.0	12.0	150	5.158	0.0	765.0	1.032	1.232	13.679	5.82
22	654.0	37.172	10.0	42.8	14.0	150	5.554	0.0	756.0	0.975	1.024	6.720	4.59
23	651.0	35.941	10.0	42.4	16.0	150	6.322	0.0	780.0	1.036	0.263	8.768	9.18
24	648.0	35.232	10.0	42.7	18.0	150	6.782	0.0	834.0	1.148	0.183	11.399	12.89
25	649.5	38.401	10.0	43.0	22.8	150	10.565	0.0	732.0	1.417	0.485	24.612	97.06

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTION TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
26	651.0	35.656	20.0	42.5	12.0	150	4.895	0.0	705.0	1.009	1.304	33.591	9.14
27	648.0	34.728	20.0	42.4	14.0	150	5.297	0.0	695.0	0.927	0.785	8.699	7.30
28	649.5	34.142	20.0	43.2	16.0	150	5.777	0.0	706.0	1.023	0.360	9.932	11.41
29	649.5	34.569	20.0	43.3	18.0	150	6.376	0.0	705.0	1.041	0.235	10.810	19.47
30	648.0	42.097	20.0	42.5	23.1	150	9.405	0.0	660.0	1.149	0.285	15.971	80.09
31	642.0	34.133	20.0	45.6	12.0	200	4.528	0.0	660.0	1.011	2.947	63.257	9.99
32	648.0	33.556	20.0	45.7	14.0	200	5.025	0.0	668.0	0.961	3.091	8.918	7.27
33	640.0	46.104	20.0	96.7	23.9	200	9.493	0.0	606.0	1.023	0.976	15.922	62.14
34	649.5	37.048	20.0	45.3	16.0	200	5.332	0.0	688.0	0.924	1.138	8.642	9.04
35	649.5	32.934	20.0	45.7	18.0	200	6.153	0.0	712.0	1.380	0.310	10.566	17.20
36	649.5	38.273	10.0	45.6	12.0	200	4.768	0.0	720.0	1.004	1.120	73.155	7.06
37	654.0	38.298	10.0	45.9	14.0	200	5.126	0.0	744.0	0.936	1.490	7.011	4.44
38	654.0	30.357	10.0	45.1	23.2	200	9.699	0.0	730.0	1.637	0.550	25.702	99.32
39	654.0	34.907	10.0	45.4	16.0	200	5.353	0.0	774.0	0.998	0.942	8.133	5.89
40	651.0	31.900	10.0	45.2	18.0	200	6.414	0.0	790.0	1.159	0.388	11.496	11.41
41	649.5	38.992	0.0	46.3	12.0	200	5.390	0.0	794.0	1.207	1.199	142.747	7.03
42	673.5	36.399	0.0	47.7	14.0	200	5.691	0.0	834.0	1.116	4.620	54.548	3.42
43	667.5	38.026	0.0	46.9	16.0	200	6.109	0.0	858.0	1.062	3.806	7.969	3.93
44	645.0	31.332	0.0	45.8	18.0	200	7.092	0.0	888.0	1.425	1.027	13.742	5.45
45	681.0	25.332	0.0	47.2	24.0	200	12.581	0.0	835.0	2.506	3.507	57.125	172.30
46	1206.0	46.543	30.0	46.2	18.0	100	5.382	2.8	860.0	0.761	7.886	9.187	6.23
47	1209.0	44.869	30.0	46.6	20.0	100	6.082	2.8	865.0	0.806	2.296	9.992	15.45
48	1206.0	45.527	30.0	46.3	22.2	100	6.821	4.1	858.0	0.461	0.750	11.643	28.71
49	1200.0	45.000	30.0	45.0	24.1	100	8.000	5.5	770.0	1.023	0.318	14.455	70.91
50	1203.0	43.435	40.0	46.2	17.9	100	5.260	2.5	895.0	0.796	4.234	9.695	8.42

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
51	1206.0	48.268	40.0	45.2	19.9	100	6.000	2.8	879.0	0.769	1.908	9.480	10.15
52	1203.0	46.627	40.0	46.4	22.0	100	6.714	4.1	890.0	0.850	0.592	11.913	22.83
53	1206.0	38.432	40.0	46.5	24.1	100	8.296	5.5	792.0	1.183	0.368	16.068	86.65
54	1203.0	46.699	25.0	46.2	18.0	100	5.468	2.8	945.0	0.787	2.306	9.037	5.89
55	1206.0	43.515	25.0	46.3	20.0	100	6.190	2.8	968.0	0.892	0.727	11.855	9.13
56	1206.0	44.934	25.0	47.3	22.0	100	7.106	5.3	985.0	0.934	0.430	15.125	18.72
57	1203.0	46.710	25.0	46.5	23.7	100	9.089	6.4	880.0	1.115	0.409	16.409	73.76
58	1206.0	43.288	15.0	45.9	17.9	100	5.726	2.8	1020.0	0.903	1.358	11.062	5.67
59	1209.0	48.962	15.0	46.8	20.0	100	6.566	4.1	1042.0	0.878	0.585	12.015	5.46
60	1209.0	42.050	15.0	47.0	22.0	100	7.716	5.5	1050.0	1.107	0.380	20.668	18.05
61	1209.0	42.560	15.0	46.9	23.6	100	9.653	8.3	970.0	1.334	0.458	24.959	87.80
62	1207.5	45.017	50.0	47.8	18.0	150	5.348	2.8	865.0	0.763	8.115	8.841	6.37
63	1209.0	44.544	50.0	47.2	20.0	150	5.894	2.8	852.0	0.793	2.527	8.852	12.13
64	1209.0	48.675	50.0	47.9	22.0	150	6.585	4.1	850.0	0.756	1.253	8.586	18.02
65	1209.0	47.117	50.0	46.4	25.2	150	8.916	5.5	749.0	0.988	0.371	11.481	77.00
66	1212.0	47.873	40.0	46.5	18.0	150	5.482	2.8	890.0	0.746	4.930	7.970	7.20
67	1213.5	44.010	40.0	46.2	20.1	150	6.105	2.8	887.0	0.836	1.205	9.500	13.56
68	1215.0	45.888	40.0	46.3	22.0	150	6.809	2.5	892.0	0.837	0.744	10.382	20.95
69	1212.0	48.518	40.0	46.5	24.6	150	8.939	3.0	5.5	0.983	0.364	11.794	75.31
70	1218.0	42.697	25.0	46.9	18.0	150	5.761	2.8	956.0	0.869	1.258	9.278	7.65
71	1213.5	43.029	25.0	46.2	20.0	150	6.283	2.8	985.0	0.910	0.767	11.104	9.28
72	1218.0	38.336	25.0	46.2	22.0	150	7.310	4.1	980.0	1.104	0.512	17.800	27.48
73	1212.0	47.693	25.0	46.8	23.9	150	9.290	6.4	860.0	1.081	0.409	15.036	74.77
74	1213.5	46.743	15.0	46.6	18.0	150	5.968	3.3	1038.0	0.857	0.942	8.890	5.00
75	1212.0	48.472	15.0	46.4	20.0	150	6.823	5.3	1055.0	0.900	0.549	10.893	5.43

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
76	1213.5	50.098	15.0	46.4	22.0	150	7.920	5.5	1070.0	0.964	0.356	15.395	10.06
77	1215.0	42.768	15.0	46.1	23.3	150	9.483	8.3	1010.0	1.269	0.357	24.061	61.39
78	1237.5	43.476	50.0	45.0	18.0	200	5.775	3.0	833.0	0.748	11.061	10.559	5.03
79	1242.0	42.043	50.0	45.0	20.0	200	6.101	3.4	860.0	0.799	5.631	12.474	8.20
80	1219.5	44.167	50.0	45.0	26.6	200	9.744	7.3	745.0	1.000	0.477	14.833	74.64
81	1215.0	47.596	50.0	45.0	22.0	200	6.721	4.0	853.0	0.719	5.146	10.417	13.13
82	1218.0	48.203	40.0	45.0	18.0	200	5.788	3.0	825.0	0.684	11.245	8.565	4.92
83	1218.0	46.407	40.0	45.0	20.0	200	6.300	3.5	875.0	0.740	3.694	10.294	7.14
84	1213.5	51.786	40.0	45.0	26.7	200	9.973	7.5	770.0	0.872	0.389	13.288	64.18
85	1218.0	47.216	40.0	45.0	22.0	200	7.172	4.5	865.0	0.748	1.700	10.901	18.53
86	1219.5	44.757	25.0	45.0	18.0	200	5.831	3.0	920.0	0.755	4.025	9.130	4.35
87	1218.0	39.420	25.0	45.0	20.0	200	6.192	3.5	935.0	0.960	2.075	14.486	6.79
88	1215.0	42.594	25.0	45.0	25.5	200	10.032	7.8	840.0	1.145	0.378	19.296	79.79
89	1230.0	43.233	25.0	45.0	22.0	200	7.331	4.9	937.0	0.863	0.485	13.994	18.02
90	1218.0	46.060	15.0	45.0	17.8	200	6.271	3.6	1020.0	0.814	2.047	9.439	2.96
91	1219.5	40.584	15.0	45.0	20.0	200	6.748	4.0	1035.0	0.925	1.281	13.868	4.02
92	1219.5	42.460	15.0	45.0	25.3	200	10.851	9.5	945.0	1.256	0.650	26.307	85.45
93	1218.0	43.885	15.0	45.0	22.0	200	7.932	6.0	1050.0	0.974	0.552	18.530	12.99
94	1212.0	101.918	40.0	47.3	18.0	100	6.831	4.6	946.0	0.499	10.022	4.455	3.80
95	1212.0	103.411	40.0	47.6	20.0	100	7.368	5.5	940.0	0.502	4.858	4.711	4.53
96	1212.0	98.300	40.0	47.4	22.0	100	8.096	6.7	938.0	0.536	1.047	5.839	8.99
97	1212.0	99.124	40.0	47.9	24.7	100	11.371	11.0	807.0	0.685	0.351	9.794	43.66
98	1219.5	97.823	25.0	47.1	18.0	100	6.987	5.5	1020.0	0.587	3.349	5.650	3.47
99	1209.0	98.517	25.0	47.2	20.0	100	7.862	8.3	1033.0	0.556	1.290	6.219	4.10
100	1209.0	95.645	25.0	47.8	22.0	100	9.247	11.0	1037.0	0.645	0.420	8.602	11.80

	SPEED	TORQUE	IGNITION TIMING	INJECTOR TIMING	AIR/FUEL RATIO	INLET AIR HEATING	MAP	EXHAUST PRESSURE	EXHAUST TEMP.	BSFC	BSNO	BSCO	
	(RPM)	(BFT-LB)	(BTDC)	(BTDC)		(DEG.)	(PSIA)	(IN-H2O)	(DEG.-F)	(LB/BHP-HR)	-----	(GM/BHP-HR)	------
101	1209.0	96.965	25.0	47.8	23.8	100	12.256	13.8	915.0	0.804	0.231	13.282	50.81
102	1206.0	98.198	15.0	47.8	18.0	100	7.284	5.5	1098.0	0.568	2.063	6.397	2.68
103	1209.0	98.024	15.0	47.2	20.0	100	8.693	8.3	1127.0	0.640	0.741	8.122	3.34
104	1212.0	98.907	15.0	47.4	22.0	100	10.301	11.0	1164.0	0.706	0.428	11.792	9.38
105	1218.0	96.458	15.0	47.5	22.7	100	12.339	16.6	1050.0	0.824	0.192	14.863	37.37
106	1219.5	95.940	40.0	48.2	18.0	150	6.795	5.5	951.0	0.521	13.932	4.561	4.30
107	1219.5	95.926	40.0	47.7	19.9	150	7.371	5.5	940.0	0.506	6.197	5.041	4.45
108	1221.0	102.468	40.0	46.8	22.0	150	8.278	8.3	932.0	0.500	2.795	5.059	5.83
109	1215.0	100.280	40.0	46.7	25.3	150	11.072	11.0	850.0	0.613	0.171	8.093	32.79
110	1213.5	99.020	25.0	47.5	18.0	150	6.966	5.5	1000.0	0.521	6.882	5.088	3.62
111	1213.5	101.492	25.0	47.5	20.0	150	7.702	5.5	995.0	0.515	2.577	5.377	3.58
112	1215.0	99.390	25.0	46.8	22.0	150	9.113	8.3	1013.0	0.576	0.524	6.599	7.90
113	1218.0	100.740	25.0	46.7	24.7	150	11.666	13.8	945.0	0.659	0.092	9.119	37.19
114	1215.0	99.852	15.0	46.7	19.6	150	7.429	5.5	1070.0	0.497	3.098	5.963	2.76
115	1215.0	99.306	15.0	46.8	20.0	150	8.238	8.3	1078.0	0.569	0.949	6.828	2.96
116	1213.5	101.869	15.0	46.4	22.0	150	9.869	11.0	1110.0	0.604	0.430	8.308	5.71
117	1213.5	87.063	15.0	46.0	24.2	150	12.595	16.6	1000.0	0.851	0.227	14.497	47.40
118	1203.0	98.770	40.0	46.8	18.0	200	7.273	5.5	920.0	0.552	14.997	4.797	4.09
119	1201.5	98.888	40.0	46.9	20.0	200	7.660	5.5	925.0	0.494	6.130	4.536	4.42
120	1203.0	102.172	40.0	46.5	22.1	200	8.170	8.3	927.0	0.475	4.253	4.642	5.34
121	1206.0	93.218	40.0	46.4	26.1	200	11.537	11.0	857.0	0.649	0.269	8.619	39.69
122	1201.5	101.638	25.0	46.5	18.0	200	7.223	4.1	995.0	0.519	7.742	5.291	3.93
123	1203.0	98.723	25.0	46.5	22.0	200	9.224	6.1	990.0	0.549	0.945	5.438	6.97
124	1201.5	98.022	25.0	46.3	20.0	200	8.109	5.5	1000.0	0.531	1.731	4.863	4.19
125	1203.0	98.144	25.0	46.2	25.1	200	12.715	13.8	892.0	0.695	0.117	9.072	41.76

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
126	1203.0	99.289	15.0	46.4	18.0	200	7.646	5.5	1070.0	0.560	3.045	6.275	2.99
127	1200.0	100.371	15.0	45.5	20.0	200	8.763	6.1	1083.0	0.580	1.194	5.845	3.37
128	1201.5	94.293	15.0	46.2	22.0	200	10.862	11.0	1115.0	0.698	0.389	9.655	11.71
129	1201.5	97.718	15.0	46.1	24.1	200	13.563	16.6	1022.0	0.793	0.224	13.623	40.02
130	2019.0	70.224	40.0	45.0	18.0	100	6.270	8.3	1115.0	0.621	11.818	8.339	2.26
131	2016.0	70.234	40.0	45.0	20.0	100	6.865	11.0	1108.0	0.592	4.331	9.322	2.41
132	1992.0	68.210	40.0	45.0	22.0	100	7.681	14.0	1096.0	0.655	1.997	10.966	8.11
133	2065.5	65.517	40.0	45.0	24.9	100	9.570	25.0	1025.0	0.838	0.692	13.956	49.61
134	2040.0	71.716	25.0	45.0	18.0	100	6.499	11.0	1202.0	0.632	5.064	8.009	0.85
135	2031.0	71.540	25.0	45.0	20.0	100	7.013	14.0	1200.0	0.662	3.109	9.835	1.08
136	2029.5	67.948	25.0	45.0	22.0	100	7.964	19.0	1220.0	0.741	1.265	13.553	3.79
137	2016.0	71.833	25.0	45.0	24.7	100	10.555	33.0	1170.0	0.895	0.724	19.276	44.75
138	2019.0	71.386	15.0	45.0	18.0	100	6.925	11.0	1317.0	0.722	4.356	5.667	0.61
139	2016.0	67.261	15.0	45.0	20.0	100	8.060	19.0	1350.0	0.810	1.586	7.649	0.36
140	2017.5	66.622	15.0	45.0	22.0	100	9.158	25.0	1390.0	0.882	1.142	10.970	0.75
141	2022.0	79.137	15.0	45.0	23.2	100	11.356	47.0	1450.0	0.908	0.852	12.181	4.45
142	2041.5	73.940	40.0	41.0	18.0	150	6.387	8.3	1180.0	0.581	10.024	8.571	1.90
143	2029.5	71.440	40.0	39.7	20.0	150	7.296	11.0	1176.0	0.615	4.157	11.101	2.04
144	2022.0	69.966	40.0	40.3	22.0	150	8.965	13.8	1175.0	0.675	1.211	14.403	7.27
145	1999.5	71.762	40.0	40.8	24.3	150	10.023	22.1	1070.0	0.758	0.395	12.657	42.19
146	2001.0	67.936	25.0	40.5	18.1	150	7.016	11.0	1250.0	0.664	3.131	7.737	1.19
147	1989.0	74.278	25.0	41.2	20.0	150	7.680	13.8	1260.0	0.657	2.117	9.750	1.12
148	1986.0	67.641	25.0	42.2	22.0	150	8.838	19.3	1285.0	0.784	0.796	15.443	4.05
149	2013.0	71.741	25.0	41.4	23.8	150	10.660	27.6	1215.0	0.856	0.525	19.543	34.71
150	2017.5	66.285	15.0	42.6	17.8	150	7.716	13.8	1360.0	0.743	2.076	5.244	0.61

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
151	2023.5	66.259	15.0	41.4	20.0	150	8.324	19.3	1400.0	0.825	1.117	7.337	0.42
152	2022.0	69.897	15.0	41.9	22.0	150	9.657	27.6	1470.0	0.882	0.774	10.862	0.68
153	2029.5	69.266	40.0	41.5	18.0	200	6.243	8.3	1175.0	0.595	11.197	8.175	1.83
154	2022.0	65.556	40.0	41.2	20.0	200	6.853	11.0	1169.0	0.626	4.496	10.198	2.66
155	2023.5	66.712	40.0	41.5	22.0	200	7.729	13.8	1170.0	0.656	1.769	11.036	6.76
156	2034.0	68.988	40.0	42.0	23.7	200	9.079	19.3	1115.0	0.719	0.870	11.161	26.44
157	2029.5	58.928	40.0	41.4	24.7	200	10.104	22.1	1025.0	0.889	0.589	13.566	67.16
158	2023.5	68.623	25.0	41.3	18.1	200	6.510	11.0	1290.0	0.644	5.602	8.383	1.23
159	2029.5	70.951	25.0	41.4	20.0	200	7.222	13.8	1250.0	0.645	2.794	9.734	1.29
160	2031.0	63.605	25.0	40.4	22.2	200	8.423	19.3	1225.0	0.771	0.867	14.531	8.47
161	2034.0	69.439	25.0	40.5	24.1	200	10.770	27.6	1115.0	0.860	0.322	16.586	47.18
162	2034.0	65.948	15.0	41.0	18.0	200	7.211	13.8	1362.0	0.740	2.355	6.392	0.73
163	2022.0	67.149	15.0	42.1	19.9	200	8.000	16.6	1385.0	0.768	1.425	8.091	0.59
164	2022.0	70.177	15.0	41.6	22.0	200	9.318	22.1	1380.0	0.816	1.026	10.975	1.12
165	2022.0	72.823	15.0	42.6	22.4	200	11.144	36.0	1450.0	0.907	0.784	19.290	9.24
166	2013.0	178.281	40.0	41.4	18.0	100	9.384	24.9	1227.0	0.405	13.103	4.942	2.02
167	2016.0	179.510	40.0	41.2	19.9	100	10.087	30.4	1218.0	0.405	6.336	5.608	2.03
168	2016.0	176.112	40.0	41.4	21.9	100	11.693	44.2	1230.0	0.449	1.594	6.298	4.51
169	2019.0	179.914	40.0	41.5	23.4	100	13.607	60.9	1040.0	0.489	0.757	6.420	17.97
170	2017.5	180.435	25.0	39.6	17.9	100	9.703	30.4	1220.0	0.421	6.915	6.211	1.06
171	2019.0	177.935	25.0	41.2	20.0	100	10.692	38.7	1225.0	0.442	3.062	7.217	0.96
172	2016.0	173.785	25.0	41.1	22.0	100	12.743	60.9	1133.0	0.510	1.061	9.125	3.28
173	2016.0	176.657	25.0	40.7	22.6	100	14.368	72.0	995.0	0.536	0.812	9.956	12.52
174	2019.0	181.415	15.0	40.9	18.0	100	10.322	41.5	1245.0	0.463	7.198	5.087	0.27
175	2016.0	177.453	15.0	41.4	20.0	100	12.756	63.5	1270.0	0.537	1.730	6.955	0.50

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INLET AIR HEATING (DEG.)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
176	2047.5	178.700	40.0	43.2	19.0	150	11.287	27.6	1055.0	0.403	11.393	5.209	1.97
177	2053.5	178.134	40.0	42.7	20.9	150	11.971	36.0	1110.0	0.409	4.718	5.704	2.07
178	2061.0	186.755	40.0	40.1	23.8	150	14.260	71.9	1010.0	0.453	1.068	5.372	12.51
179	2016.0	178.781	25.0	40.7	19.0	150	11.765	36.0	1080.0	0.430	6.272	6.658	1.01
180	2016.0	178.306	25.0	41.4	21.1	150	12.882	49.8	1010.0	0.465	1.722	7.580	1.64
181	2016.0	182.557	15.0	41.1	18.0	150	12.037	41.5	1105.0	0.458	5.799	5.556	0.23
182	2013.0	178.692	15.0	41.1	20.0	150	12.952	52.6	1115.0	0.497	2.137	6.780	0.30
183	2011.5	176.720	15.0	40.7	20.7	150	13.563	58.1	1050.0	0.513	2.676	8.534	1.04
184	2013.0	182.451	15.0	41.9	18.0	200	12.521	44.0	1063.0	0.480	5.036	6.046	0.23
185	2013.0	181.702	15.0	41.4	19.9	200	13.193	50.0	1050.0	0.468	2.677	6.760	0.30
186	2013.0	177.167	25.0	40.3	18.0	200	11.611	33.0	955.0	0.429	7.019	6.385	0.73
187	2013.0	174.966	25.0	40.0	20.1	200	12.296	39.0	970.0	0.440	3.530	7.099	0.91
188	2016.0	184.132	25.0	40.0	21.3	200	13.402	50.0	940.0	0.452	1.882	7.075	1.74
189	2016.0	176.479	40.0	39.1	18.0	200	11.149	28.0	895.0	0.411	17.504	4.516	1.97
190	2017.5	175.952	40.0	40.9	20.0	200	12.165	36.0	875.0	0.425	4.360	5.239	2.13
191	2017.5	176.777	40.0	40.8	22.0	200	12.865	44.0	897.0	0.433	2.509	5.544	3.22
192	2016.0	165.435	40.0	38.9	23.3	200	14.235	53.0	859.0	0.487	0.996	5.602	14.27

F.6

INTAKE VALVE THROTTLING

A 100 LB/HR @ 640 RPM CAM

B 400 LB/HR @ 1200 RPM CAM

C 800 LB/HR @ 2000 RPM CAM

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INTAKE THROTTLING (CAM)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
1	640.0	35.000	0.0	45.0	12.3	A	13.800	1.5	687.0	1.193	2.349	346.029	16.64
2	640.0	35.000	10.0	45.0	12.7	A	13.500	1.4	619.0	1.060	3.638	208.162	18.47
3	640.0	35.000	20.0	45.0	12.6	A	13.600	1.4	562.0	1.050	3.665	188.111	20.75
4	640.0	35.000	20.0	45.0	14.5	A	14.000	1.4	565.0	1.025	3.482	66.114	18.71
5	640.0	35.000	10.0	45.0	14.5	A	13.900	1.3	625.0	1.029	2.374	56.269	14.64
6	640.0	35.000	0.0	45.0	14.3	A	14.200	1.6	693.0	1.135	1.982	93.487	11.31
7	640.0	37.212	0.0	45.0	16.0	B	6.851	0.0	770.0	1.190	1.419	4.047	5.81
8	640.0	36.196	0.0	45.0	18.0	B	7.791	0.0	800.0	1.274	0.704	5.989	8.31
9	640.0	33.538	0.0	45.0	20.0	B	8.970	0.0	845.0	1.498	0.564	10.930	16.92
10	640.0	32.925	0.0	45.0	22.0	B	10.836	0.0	838.0	1.778	0.732	18.270	78.09
11	640.0	38.033	10.0	45.0	16.0	B	5.978	0.0	690.0	0.889	0.982	5.866	10.27
12	640.0	34.173	10.0	45.0	18.0	B	7.031	0.0	695.0	1.148	0.449	8.723	24.33
13	640.0	25.294	10.0	45.0	20.0	B	10.203	0.0	605.0	2.054	0.785	19.105	125.70
14	1200.0	46.198	20.0	45.0	18.0	B	7.162	2.8	866.0	0.766	5.605	6.454	8.53
15	1200.0	43.993	20.0	45.0	20.0	B	7.898	3.2	868.0	0.823	1.412	7.722	17.55
16	1200.0	44.657	20.0	45.0	22.0	B	9.347	5.6	825.0	0.909	0.455	9.681	43.23
17	1200.0	39.995	20.0	45.0	23.0	B	10.084	5.8	760.0	1.075	0.480	12.658	71.32
18	1200.0	47.987	25.0	45.0	18.0	B	7.275	2.8	852.0	0.756	7.960	6.429	10.17
19	1200.0	47.066	25.0	45.0	20.0	B	7.917	3.2	840.0	0.782	2.505	7.060	17.40
20	1200.0	43.127	25.0	45.9	22.0	B	8.901	5.6	790.0	0.894	0.535	9.150	43.68
21	1200.0	43.251	25.0	45.0	23.0	B	9.889	5.8	740.0	0.973	0.336	10.583	61.18
22	1200.0	48.987	15.0	45.9	18.0	B	7.630	3.4	906.0	0.798	2.340	6.973	9.77
23	1200.0	43.151	15.0	45.0	20.0	B	8.478	5.6	895.0	0.928	0.687	9.092	23.20
24	1200.0	42.951	15.0	45.0	22.0	B	9.930	5.8	840.0	1.043	0.449	11.611	56.82
25	1200.0	100.669	15.0	45.0	20.0	B	10.787	6.2	970.0	0.534	3.521	3.201	6.54

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INTAKE THROTTLING (CAM)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
26	1200.0	101.383	15.0	45.0	18.0	B	9.892	5.6	982.0	0.524	1.867	3.117	4.43
27	1200.0	101.583	15.0	45.0	22.0	B	11.970	7.0	954.0	0.555	1.334	3.730	13.30
28	1200.0	103.596	15.0	45.0	23.4	B	13.765	11.2	862.0	0.621	0.406	4.629	34.00
29	1200.0	102.971	25.0	45.0	20.0	B	10.455	5.6	900.0	0.498	2.215	3.218	6.27
30	1200.0	102.700	25.0	45.0	22.0	B	11.140	6.3	880.0	0.504	0.996	3.415	9.60
31	1200.0	96.843	25.0	45.0	24.7	B	13.811	11.2	738.0	0.621	0.648	5.020	39.68
32	1200.0	102.400	40.0	45.0	22.0	B	11.495	7.0	838.0	0.505	3.214	3.404	8.83
33	1200.0	100.635	40.0	45.0	24.0	B	12.161	7.0	792.0	0.518	0.962	3.979	17.63
34	1200.0	98.897	40.0	45.0	26.0	B	13.487	10.6	710.0	0.572	0.586	4.799	36.31
35	2000.0	72.256	30.0	45.0	18.0	B	11.566	8.3	960.0	0.607	21.967	6.035	4.24
36	2000.0	71.810	30.0	45.0	20.0	B	12.344	11.1	945.0	0.595	13.744	6.472	5.89
37	2000.0	66.846	30.0	45.0	22.0	B	13.419	13.9	915.0	0.651	3.649	6.551	17.41
38	2000.0	67.851	30.0	45.0	23.9	B	14.691	16.6	840.0	0.682	2.452	7.412	34.76
39	2000.0	69.943	25.0	45.0	18.0	B	11.480	8.3	970.0	0.613	17.043	7.059	4.22
40	2000.0	72.584	25.0	45.0	20.0	B	12.580	13.9	984.0	0.601	7.532	6.709	6.04
41	2000.0	67.997	25.0	45.0	22.0	B	13.581	16.6	923.0	0.653	2.456	6.925	16.31
42	2000.0	72.757	25.0	45.0	23.4	B	14.671	16.6	900.0	0.652	2.311	6.797	32.03
43	2000.0	72.848	15.0	45.0	18.0	B	12.051	11.1	1070.0	0.627	8.386	8.319	20.09
44	2000.0	69.080	15.0	45.0	20.0	B	13.581	16.6	1050.0	0.676	2.362	10.051	6.57
45	2000.0	71.996	15.0	45.0	21.9	B	14.690	19.4	1005.0	0.694	1.597	9.851	18.73
46	2000.0	178.719	30.0	45.0	19.0	C	10.323	27.7	1156.0	0.420	17.149	3.586	2.17
47	2000.0	177.709	30.0	45.0	21.0	C	11.219	33.2	1110.0	0.421	9.048	3.781	2.40
48	2000.0	182.048	30.0	45.0	23.0	C	12.519	41.5	1050.0	0.422	2.331	3.516	3.98
49	2000.0	177.838	30.0	45.0	24.0	C	12.907	47.0	1050.0	0.437	1.263	3.555	5.84
50	2000.0	183.957	25.0	45.0	18.0	C	10.156	26.3	1202.0	0.413	15.537	3.753	1.79

	SPEED (RPM)	TORQUE (BFT-LB)	IGNITION TIMING (BTDC)	INJECTOR TIMING (BTDC)	AIR/FUEL RATIO	INTAKE THROTTLING (CAM)	MAP (PSIA)	EXHAUST PRESSURE (IN-H2O)	EXHAUST TEMP. (DEG.-F)	BSFC (LB/BHP-HR)	BSNO -----	BSCO (GM/BHP-HR)	BSHC ------
51	2000.0	182.503	25.0	45.0	20.0	C	10.834	30.5	1194.0	0.415	11.661	4.506	1.65
52	2000.0	182.376	25.0	45.0	22.0	C	12.065	41.6	1165.0	0.428	3.263	4.264	2.29
53	2000.0	182.487	25.0	45.0	23.0	C	12.684	44.3	1125.0	0.441	3.578	3.616	3.79
54	2000.0	186.778	15.0	45.0	17.0	C	10.504	30.5	1250.0	0.431	15.772	4.725	0.96
55	2000.0	184.375	15.0	45.0	20.0	C	11.223	38.8	1219.0	0.437	6.741	6.016	2.80
56	2000.0	175.039	15.0	45.0	22.0	C	12.541	47.0	1195.0	0.464	1.862	5.264	6.87

Assuming the same cylinder pressure exists for the inlet valve throttling case, the valve lift was found to be:

$$x = \frac{0.06551\sqrt{760}}{0.65\ (2.037)\ \pi\ (14.4)\ (0.532)\ f_1 \left(\frac{10.46}{14.4}\right)}$$

$$= 0.06235 \text{ inch}$$

and the camshaft lift is:

$$\ell = \frac{0.0624}{1.75}$$

$$= 0.0357 \text{ inch}$$

By similar analysis, the average valve flow rate at 800 lbs/hr is:

$$W_8 = 0.1308 \text{ lbs/sec}$$

$$P_4 = 11.1 \text{ psia}$$

$$x = 0.1455 \text{ inch}$$

and

$$\ell = 0.0832 \text{ inch}$$

If the cylinder pressure is such that critical conditions exist across the inlet port for the 400 and 800 lbs/hr camshafts, the flow into the cylinders will be increased. The 400 and 800 lbs/hr camshafts will then result in maximum flow rates of 440 and 930 lbs/hr. The actual flow rates will lie somewhere between 400 and 440 lbs/hr in the one case and 800 and 930 lbs/hr for the other case. Since throttling, in the conventional sense, was suggested as a method for final adjustment of the air flow rates, it appeared that the cam profiles computed would be satisfactory.

The actual lift values versus camshaft position for all three profiles are shown in Tables E-1, E-2, and E-3. This format is typical and was sufficient for a cam grinding vendor to generate the desired camshafts.